MODELLING OF MAXIMAL AND SUBMAXIMAL OXYGEN UPTAKE IN MEN AND WOMEN.

BY

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ABSTRACT

Confounding the findings of most studies comparing maximal and sub-maximal oxygen uptake ($\dot{V}O_2$) of men and women is the inappropriate use of the ratio standard ($ml \cdot kg^{-1} \cdot min^{-1}$) to remove the influence of body size. Non-linear allometric modelling has been shown to be a superior alternative. Therefore, the purpose of these studies was to investigate the use of the ratio standard and non-linear allometric modelling to remove the influence of body size and so allow meaningful gender comparisons of sub-maximal and maximal $\dot{V}O_2$.

The purpose of study **1** was to compare $\dot{V}O_{2\,max}$ in 17 male and 17 female distance runners. The ratio standard was found to be inappropriate and distorted the data. Non-linear allometric modelling correctly scaled values for $\dot{V}O_{2\,max}$. Pooled body size exponents (± SEE) were identified; 0.94 (± 0.12) for body mass (BM) and 0.98 (± 0.10) for fat free mass (FFM), and a gender difference in $\dot{V}O_{2\,max}$ was found. The difference was estimated at 24.5 % using BM as the body size variable and 9.6 % using FFM, with men having the higher values.

The purpose of study **2** was to compare $\dot{V}O_{2\,max}$ in 50 male and 69 female International standard endurance athletes. The ratio standard distorted values for $\dot{V}O_{2\,max}$ and created an artificial difference between endurance sports. The allometric model successfully scaled $\dot{V}O_{2\,max}$ and was further improved by the addition of age as a covariate. Pooled body size exponents were identified; 0.68 (± 0.04) for BM and 0.80 (± 0.04) for FFM, and a gender difference in $\dot{V}O_{2\,max}$ was identified but no difference was found between endurance sports. Maximal oxygen uptake in men was, on average, 29.4 % higher than women using BM mass as the body size variable and 15.3 % higher using FFM.

The purpose of study **3** was to investigate the age-associated decline of $\dot{V}O_{2\,max}$ in older humans (152 men & 146 women), aged 55 – 86 years. Allometric modelling successfully scaled values of $\dot{V}O_{2\,max}$ independent of body size and age and was further improved by the addition of physical activity. Pooled body size exponents were identified; 0.58 (± 0.07) for BM and 0.96 (± 0.05) for FFM. Age-associated decline of $\dot{V}O_{2\,max}$ in later life was estimated at ≈ 1.5 % per year. Using FFM as the body size variable, no gender difference in $\dot{V}O_{2\,max}$ was identified.

The purpose of study **4** was to investigate sub-maximal $\dot{V}O_2$ in 17 male and 17 female distance-runners. The ratio standard distorted values for $\dot{V}O_2$ and created an artificial gender difference. The allometric model successfully scaled $\dot{V}O_2$ and pooled body size exponents were identified; 0.75 (± 0.05) for BM and 0.50 (± 0.04) for FFM. Using either body size variable (BM & FFM), no gender difference in sub-maximal $\dot{V}O_2$ was found.

Overall, the ratio standard was found to distort the data and was an inappropriate scaling method. Non-linear allometric modelling was an appropriate method for scaling sub-maximal and maximal $\dot{V}O_2$. For meaningful gender comparison the use of FFM mass, in preference to BM, was recommended as it removed the within-participant and gender differences in body composition.

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Chapter 1

INTRODUCTION

Measurement of oxygen uptake is a cornerstone in physiology. Based on the premise that metabolism ultimately depends on the utilization of oxygen (Priestley, 1864, *cited* Thompson, 1959), such measurement has become common as an indirect estimate of energy expenditure. The higher the oxygen uptake ($\dot{V}O_2$), the higher the energy expenditure and thus human endurance is limited by the ability to consume oxygen (Hill & Lupton, 1923; Hill, Long & Lupton, 1924).

Interest in comparing the aerobic capabilities of men and women has a long history (Hill, 1925) and with increased participation in sport and exercise by women, this interest has assumed greater prominence. For example, as women tend to have a lower maximal oxygen uptake ($\dot{V}O_{2\,max}$) per unit of body mass than men, this difference, in some part, has been attributed to their inferior endurance performance (Wilmore & Brown, 1974).

At rest and during any form of activity, a person's oxygen uptake ($\dot{V}O_2$) is influenced by the amount of metabolically active tissue (Åstrand & Rodahl, 1986). In general, the bigger you are the greater your metabolically active tissue and so the higher your oxygen uptake. As men tend to be bigger than women this difference in body size needs to be removed before meaningful gender comparison of the aerobic qualitative characteristics of tissues can be achieved. This adjustment is called scaling (Schmidt-Nielsen, 1984).

Traditionally, differences in body size have been assumed to have been removed by the construction of ratio standards, where $\dot{V}O_2$ is simply divided by body mass and expressed as $ml \cdot kg^{-1} \cdot min^{-1}$. However, the use of these simple ratios has been strongly criticised by Tanner (1949), and more recently, in the exercise sciences, by authors such as Katch (1972, 1973), Katch & Katch (1974), Nevill, Ramsbottom and Williams (1992), Winter (1992), Nevill and Holder (1994), Vanderburgh, Katch, Schoenleber, Balabinis and Elliott (1996), Welsman, Armstrong, Nevill, Winter and Kirby (1996) and Batterham, George and Mullineaux (1997). In the example of maximal oxygen uptake ($\dot{V}O_{2\,max}$), their criticism is that unless under exceptional circumstances, as laid down by Tanner (1949), this use of a ratio-per weight standard distorts the data such that '...smaller individuals receive an arithmetic advantage while larger individuals are penalized' (Welsman *et al.*, 1996, *p*. 259). This is especially so when there are big group differences in body size, such as in comparisons between men and women (Winter, 1992).

Schmidt-Nielsen (1984) demonstrated that not all relationships between variables are linear and suggested that in humans, as in other animals, body proportions change with increases in body size. This curvilinear relationship is termed non-isometric (Packard & Boardman, 1987) and authors such as Huxley

(1932) and, more recently, Schmidt-Nielsen (1984) have advocated the use of a non-linear technique called allometry to investigate such relationships. More recently, authors such as Winter (1992), Nevill *et al.* (1992), Vanderburgh *et al.* (1996), Batterham *et al.* (1997) and Armstrong, Welsman and Kirby (1998) have successfully used allometry to remove the influence of body size from some physiological measure. However, little work has been reported on the use of non-linear allometric modelling to compare sub-maximal and maximal oxygen uptake in men and women.

Therefore the purpose of this study was to investigate the use of the ratio standard and non-linear allometric modelling to remove the influence of body size and so allow meaningful comparisons of sub-maximal and maximal oxygen uptake of men and women.

Chapter 2

REVIEW OF LITERATURE

Owing to increasing social, cultural and legislative changes (Cureton, Hensley & Tiburzi, 1979) women's participation in sporting activities is continually increasing (Wells, 1991). For example, the number of women participating in middle- and long-distance running events has increased considerably and as a result, the sport '...has undergone remarkable growth and change' (Pate, Sparling, Wilson, Cureton & Miller, 1987, *p*. 91). This increasing participation continues to stimulate interest in the comparisons between the physiological and performance capabilities of men and women.

For instance, from the 1960s through to the 1980s, the rate of improvement in athletics world records for women far exceeded that of the men. This searing progression in women's performance prompted predictions of impending equality in many sporting events (Bam, Noakes, Juritz & Dennis, 1997; Whipp & Ward, 1992;

Dyer & Dwyer, 1984; Dyer, 1982) and in the '...open Olympics of the future we are told to expect women to stand alone on the winner's podium' (Davis, Kimmet & Auty, 1986, *p.* 378). More recently, however, it has been suggested that part of this searing progression, especially in the more impulsive events, such as sprinting, was due to the use of illegal substances such as testosterone, growth hormone and steroids thereby '...directing their bodies metabolism towards 'maleness'...' (Davis *et al.*, 1986, *p.* 378). This is evident from the slower rate of improvement in women's athletics, especially in the more impulsive sports, such as sprinting and field events, since the advent of more stringent drug testing.

Table 2·1 Men and women's world records in outdoor track running events as at June 2002.

Event	Men	Women
100 m	9.79	10.49
200 m	19.32	21.34
400 m	43.18	47.60
800 m	1:41.11	1:53.28
1000 m	2:11.96	2:28.98
1500 m	3:26.00	3:50.46
Mile	3:43.13	4:12.56
3000 m	7:20.67	8:06.11
5000 m	12:39.36	14:28.09
10000 m	26:22.75	29:31.78

Source: British Athletics

Nonetheless, in sports that demand high intensities of exercise, such as distance-runners, differences between men and women remain. This is demonstrated in Table 2·1, which lists the current world records (British Athletics, 2002) in athletic running events. Such differences in performance can be partly attributed to distinct morphological and physiological differences.

GENDER DIFFERENCES

Of the approximately 10 trillion cells that comprise the human body, only those that make up the reproductive system differ in men and women (Wells, 1991). Differences include certain interrelated morphological and physiological differences that have been attributed in some part to gender differences in performance.

Body size

On average, men are 6 % taller and 19 % heavier than women (Behnke, 1969) and subsequently are not as strong (Åstrand & Rodahl, 1986). The most likely explanation for this difference, which is especially apparent during puberty, '...is the greater secretion of the hormone testosterone in the male' (Åstrand & Rodahl, *p*. 344, 1986).

Body composition

Owing to a greater percentage of essential, sex-specific body-fat, women tend to have a greater proportion of overall body-fat (Lamb, 1984). As '...body-fat adds to the mass of a subject without contributing to its force or energy-producing capabilities...' (Cureton *et al.*, 1979, *p*. 334), the greater proportion of body fat in women reduces their ability to perform. For instance, Sparling and Cureton (1983) reported that 74 % of the gender difference in a 12-minute run exercise was due to women's greater proportion of body fat. Similar findings have been reported by Cureton and Sparling (1980) and Cureton *et al.* (1979).

Haemoglobin

Haemoglobin '...increases the blood's oxygen-carrying capacity 65 to 70 times above that normally dissolved in plasma...' (McArdle, Katch & Katch, 1991, *p.* 260). The average blood concentration of haemoglobin in men (160 $g \cdot l^{-1}$) is higher than average values for women (140 $g \cdot l^{-1}$) (Rowland, 1991). This '...apparent "sex-difference" may account to some degree for the lower maximal aerobic capacity of women, even after considering differences in body weight and fat' (McArdle *et al.*, 1991, *p.* 261).

However, Pate, Barnes and Miller (1982) concluded that the higher haemoglobin concentrations measured in men might be partly offset by a higher concentration of 2,3-diphosphoglycerate. Higher levels of 2,3-diphosphoglycerate shift the oxyhaemoglobin dissociation curve further to the right increasing the bloods ability to unload oxygen at the tissues (Dempsey, Rodriquez, Shahidi, Reddau & MacDougall, 1971).

Heart size

It has been suggested that the gender difference in endurance performance is primarily related to differences in heart size (Åstrand & Rodahl, 1986; Åstrand, Cuddy, Saltin & Stenberg, 1964). Hutchinson, Cureton, Outz and Wilson (1991) reported that the difference in heart size accounted for 68 % of the gender difference in maximal physiological capacity. Although, they finally concluded that '...heart size differences between men and women are only a reflection of the general body size differences' (*p*. 373).

OXYGEN HANDLING CAPABILITY

One of the cornerstones of the physiology of exercise is the measurement of oxygen uptake as an indirect estimate of metabolism. Further, energy expenditure can be estimated from a participant's oxygen uptake and thus the physiological stress imposed by exercise can be determined. Since the early work completed by Hill and Lupton (1923) and Furusawa, Hill, Long and Lupton (1924) the limits of human endurance have been associated with the ability to extract, transport and utilise oxygen maximally (Costill, Thomason & Roberts, 1973).

Maximal oxygen uptake

More recently, a number of studies have demonstrated a positive relationship between $\dot{V}O_{2\,max}$ and middle- and long-distance running performance (Ramsbottom, Williams, Boobis & Freeman, 1989; Housch, Thorland, Pohnson, Hughes & Cisar, 1988; Pate *et al.*, 1987). Female distance-runners tend to exhibit a lower $\dot{V}O_{2\,max}$, per given unit of body mass, than their male counterparts (Padilla, Bourdin, Barthélémy & Lacour, 1992; Daniels & Daniels, 1992; Saltin & Åstrand, 1967). This has been attributed in some part to their inferior running performance. Daniels and Daniels (1992), comparing elite male and female elite middle- and long-distance runners, reported that $\dot{V}O_{2\,max}$ in the men was 14 % higher than the women (75.4 & 66.2 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively). They concluded that '...one thing seems quite clear - elite male runners have a decided aerobic advantage over elite female runners; they have a better aerobic profile' (*p*. 487). The same 'aerobic advantage' in men over women has been reported for participants in other physical and sporting activities (Bourdin, Pastene, Germain & Lacour, 1993, Cunningham, 1990; Hagerman, 1984), recreational runners (Pate, Macera, Bailey, Bartoli and Powell, 1992; Ramsbottom *et al.*, 1989), untrained subjects (Bransford & Howley, 1977) and older and ageing populations (´strand, 1960; Gerstenblith, Lakatta & Weisfeldt, 1976; Grimby & Saltin, 1966).

However, women tend to have a greater proportion of sex-specific body fat, reducing their proportion of lean muscle, which is the greatest consumer of oxygen during exercising. Body mass (BM) makes no account for this gender difference, so any comparison made using body mass gives men an advantage. Gitin, Olerud and Carroll (1974) suggested that a 'mathematical adiposectomy' [$\dot{V}O_{2\max} = \dot{V}O_2$ /(body mass (kg) - fat (kg))] would make for a more equitable comparison of $\dot{V}O_{2\max}$ in groups with a large variation in body composition. This 'mathematical adiposectomy' is body mass minus the fat mass, termed fat-free mass (FFM), and should be a more appropriate measure of body size because it better reflects the body's metabolically active tissue.

When $\dot{V}O_{2\max}$ has been adjusted for differences in fat free mass, any gender difference, identified when using body mass as the body size variable, has either been reduced or even eliminated. For example, Cureton and Sparling (1980) reported an 11 % gender difference in $\dot{V}O_{2\max}$ when comparison was made using body mass (61.7 & 55.7 $ml \cdot kg^{-1} \cdot min^{-1}$ for the men & women respectively). However, once body mass was replaced by fat free mass as the body size variable, no gender difference in $\dot{V}O_{2\max}$ was identified (69.8 & 68.9 $ml \cdot FFM^{-1} \cdot min^{-1}$, respectively). Similar findings were made when Pate *et al.* (1982) matched 8 female and 8 male distance runners for percentage body fat and time of a 15-mile road running race. Sparling and Cureton (1983) found that the difference in men and women runners in $\dot{V}O_{2\,max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) was reduced from 18 % to just 5 % after adjusting for differences in body fat.

Sub-maximal oxygen uptake

In aerobically trained athletes, the sub-maximal oxygen cost of a particular intensity of exercise, or economy, has been found to be a better indicator of performance (Conley & Krahenbuhl, 1980; Costill *et al.*, 1973) especially in homogeneous groups of runners (Daniels & Daniels, 1992). Economy in distance-running is defined as the '...relationship between oxygen consumption and velocity of running, or as the aerobic demands of running' (Daniels & Daniels, 1992, *p.* 483). The number of factors reported to affect running economy include: age (Åstrand, 1952), training (Bransford & Howley, 1977; Conley, Krahenbuhl & Burkett, 1981; Daniels 1985), stride rate and frequency (Högberg, 1952, *cited* Daniels, 1985) and shoe weight (Fredrick, Daniels & Hayes 1984, *cited* Daniels, 1985). Adults have also been found to be more economical than children (Rowland, Auchinachie, Keene & Green, 1987; Rowland & Green, 1988), although interestingly, the difference in running economy found by Rowland and Green (1988) disappeared when related to surface area. However there is considerable conflict in the numerous studies that have investigated running economy between men and women.

Bransford and Howley (1977) reported that trained male runners were more economical than trained female runners. Although, criticisms have been expressed as to the validity of their findings because comparisons were based on unequally trained subjects (Daniels & Daniels, 1992; Hopkins & Powers, 1982), which is evident in the lower than expected mean $\dot{V}O_{2\,max}$ value for the trained female runners (48.8 ml·kg^{-1}·min^{-1}). However, even when elite male and female distance runners were matched in terms of training and experience, differences have still been found. Daniels and Daniels (1992) concluded that elite male runners are more economical than elite female runners at common sub-maximal speeds. Similarly, in a sample of recreational runners, Ramsbottom *et al.* (1989) also found the men to be more economical than the women.

However, other studies have demonstrated no difference in running economy between equally matched men and women. Hopkins and Powers (1982) used '...matched pairs of highly trained male and female runners' (*p.* 130), similar to the study of Daniels and Daniels (1992), but in contrast '...found no sex differences in the oxygen cost of running' (*p.* 130). Similar results have also been reported by Pate *et al.* (1992, 1982), Cunningham (1990) and Sparling and Cureton (1983).

In summary, men were found to have a higher $\dot{V}O_{2\,max}$ (ml·kg^{-1}·min^{-1}) than women, although, this gender difference was either reduced or eliminated when fat free mass was adopted as the measure of body size. Owing to conflicting findings, gender differences in sub-maximal $\dot{V}O_2$ are still unclear.

ADJUSTING FOR SIZE

One problem in comparison of $\dot{V}O_2$ is caused by differences in body size. Energy expenditure and thus oxygen consumption is influenced by the amount of metabolically active tissue (Åstrand & Rodahl, 1986). In general, the bigger you are the greater your metabolically active tissue and so the higher your sub-maximal and maximal $\dot{V}O_2$. As men tend to be bigger than women this influence of body size needs to be known and accounted for to allow meaningful comparison. Such adjustment is called scaling (Schmidt-Nielsen, 1984).

Ratio standards

Differences in body size have conventionally been assumed to be scaled by simply dividing the physiological variable (*y*) by some appropriate measure of body size (*x*) to construct their ratio $\left(\frac{y}{x}\right)$. When plotted against the physiological variable, this ratio yields a straight line, which passes through the origin (Katch, 1973) and can be mathematically expressed as:

$$y = a \cdot x \qquad [1]$$

This assumes that the physiological variable (*y*) is directly proportional to some measure of body size (*x*) to the ratio *a*. Thus a doubling of *y* should result in doubling of *x* (Packard & Boardman, 1987). The coefficient *a*, known as the constant multiplier, is used to make comparisons between or within groups and identify the standards against which others can be compared.

However, the use of such ratio standards has been strongly criticised as early as 1897, by Karl Pearson (*cited* Tanner, 1949). The problem is that unless exceptional circumstances are satisfied (Tanner, 1949), these ratio standards fail to remove the influence of body size and have been shown to distort the data so lead to misinterpretation (Armstrong, Welsman & Kirby, 1998; Bergh, Sjödin, Forsberg & Svedenhag, 1991; Nevill *et al.*, 1992; Vanderburgh & Mahar, 1995; Welsman *et al.*, 1996). This is especially the case when intra- or inter-group differences in body size are marked, such as in comparisons between men and women or children and adults (Winter, 1992; Armstrong & Welsman, 1994).

However, in some measures ratio standards may well be justified and this is what Tanner (1949) meant by his 'special circumstance'. Tanner (1949) suggested that ratio standards are appropriate when the condition $\frac{V_x}{V_y} = r_{xy}$ is satisfied, where V_x is the coefficient of variation of the body size variable, V_y is the coefficient of variation of the physiological variable and r_{xy} is Pearson's product-moment correlation coefficient between the variables. Plotting and correlating the ratio standard scaled values against the body size variable can easily check for this 'special circumstance'. As illustrated in Figure 2·1, if the data have not been distorted then no relationship should be detected and the scaled values are truly independent of body size. If a negative or positive relationship is identified then the scaled values are not independent of body size and distortion has occurred.

Ratio standards tend to 'over-scale' values for $\dot{V}O_2$ and '...distort the data under scrutiny by conferring an arithmetic advantage on small values of x and an arithmetic disadvantage on large values of x' (Winter, 1996, *pp.* 673-674). Therefore, in comparisons between men and women, where there are big differences in body size, values of $\dot{V}O_2$ expressed as a ratio standard (ml·kg^{-1}·min^{-1}) will always be overestimated for women and underestimated for men. In terms of $\dot{V}O_{2\,max}$, this distortion will artificially inflate scaled values for women and deflate values for men, thus reducing any actual gender difference. However, the opposite will occur in gender comparison of sub-maximal $\dot{V}O_2$. Here the scaled values for women will still be artificially inflated but this will have the effect of making them appear less economical.

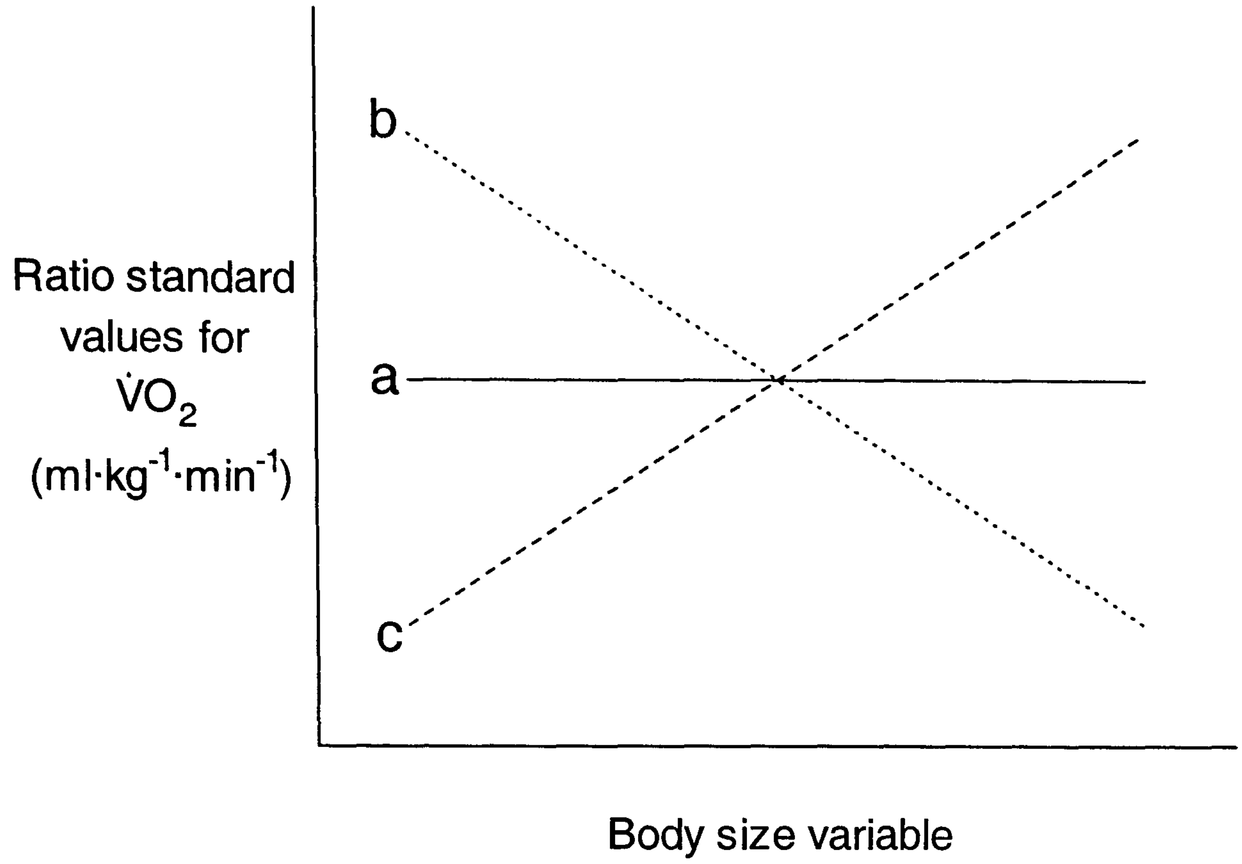

Figure 2·1 Possible relationships between ratio standard values for $\dot{V}O_2$ and body size. Example **a** demonstrates no relationship and confirms that $\dot{V}O_2$ had been correctly scaled. The negative relationship in **b** indicates that $\dot{V}O_2$ had been 'over-scaled' with the positive relationship in **c** indicating 'under-scaling'. Both **b** and **c** are inappropriate and would lead to distortion of the data.

In contrast, the scaled values for men will be underestimated making them appear more economical. This distortion, caused by using an inappropriate scaling technique, may have led to conflicting findings being reported on gender differences in sub-maximal $\dot{V}O_2$.

Linear regression model

In preference to the ratio standards, Tanner (1949) and later Katch (1972, 1973) and Katch and Katch (1974) advocated the use of linear regression expressed, in the form:

$$y = a + b \cdot x$$

with slope *b* and intercept *a*. Group comparisons can now be made using analysis of covariance (ANCOVA), which, further to satisfying certain assumptions such as homogeneity of variance and commonality of slopes, can be used to calculate adjusted means, which should now be free from the influence of body size (Snedecor & Cochran, 1980). An example of superiority of this linear model over the conventional ratio standard was presented by Winter, Hamley and Brookes (1991). They investigated maximal intensity exercise performance and lean leg volume in men and women. The use of the ratio standard revealed no gender difference. However, use of a linear regression model revealed two distinct groups, which was explained by a gender difference and suggested that '...consideration of ratio standards is misleading and that a comparison of regression standards is more appropriate' (*p*. 3).

Although this linear regression approach represents an improvement on the ratio per-weight standards, Nevill and Holder (1995) identified a number of troublesome aspects. First, '...one possible cause for concern when using linear regression to model per ratio variables is that the variance of the error term may not be constant throughout the range of observation' (*p*. 1028) which would contravene the use of a parametric test. Nevill and Holder (1995) reinforced their concern by highlighting the multiplicative value of the error, or heteroscedasticity, in previous studies conducted by Toth, Goran, Ades, Howard and Poehlman (1993) and Baxter-Jones, Feldman and Fredberg (1987, *cited* Nevill & Holder, 1995) and concluded that '...in both these examples, the error variance appears to increase in proportion to $\dot{V}O_{2\,max}$' (*p*. 1028). In accordance with their observations, similar findings have also been reported by Welsman *et al*. (1996) and Nevill and Holder (1994).

The other concern expressed by Nevill and Holder (1995) was that it is not unusual to have a positive, or negative, intercept in the regression line indicating a physiological response for no size and this '..."something for nothing" creates unease' (Winter, 1992, *p*. 299). More importantly, as Nevill *et al.* (1992, *p*. 110) stated '...if the model that describes this relationship is a true linear proportion, then the least-squares linear regression line should pass close to, if not through, the origin'. A non-zero intercept, they concluded, is symptomatic of a non-linear relationship. Schmidt-Nielsen (1984) illustrated that not all relationships between variables are necessarily linear and suggested that in humans, as in other animals, body proportions change with increases in body size. This curvilinear relationship is termed non-isometric (Packard & Boardman, 1987) and authors such as Huxley (1932) and, more recently, Schmidt-Nielsen (1984) have advocated the use of allometry to investigate such relationships.

Allometry

Schimdt-Nielsen (1984) clearly demonstrated that not all relationships are linear, and when a relationship is curvilinear the variables are said to vary allometrically (Packard & Boardman, 1987). In the field of biology and zoology there is a long established tradition of the use of allometry (from the Greek *allios*, which means to change) to investigate such relationships (Schimdt-Nielsen, 1984). Allometry scales a physiological (or dependent) variable (y) in relation to body size (or independent variable) (x) using the equation:

$$y = a \cdot x^b \qquad [2]$$

where a is the constant multiplier and b the exponent. A linear function can be constructed by taking the natural logarithm (*ln*) of each variable, represented in the form:

$$lny = lna + b \cdot lnx \qquad [3]$$

The advantage of the logarithmic transformation is the constant multiplier a and exponent b in equation [2] can now be estimated using linear regression, with slope b of the regression line and a identified by the exponentiation of the intercept, $ln(a)$. Consequently, raw values of y can now be divided by the equivalent raw values of x raised to the exponent b $\left(\frac{y}{x^b}\right)$, producing power function ratios that express values for y free from the influence of x (Kleiber, 1950). The flexibility of these power function ratios is such that when the value of the exponent $b = 1$ this satisfies Tanner's (1949) 'special circumstance' and justifies the use of a ratio standard. A caveat to this justification is the identification of a correct error structure, which in a linear model of this type is assumed to be additive.

Introducing $\dot{V}O_{2\,max}$ and body mass into equation [2], the following model was proposed by Nevill *et al.* (1992):

$$\dot{V}O_{2\,max} = a \cdot BM^b \qquad [4]$$

Thus values of $\dot{V}O_{2\,max}$ can now be expressed as power function ratios $\left(\frac{\dot{V}O_2max}{BM^b}\right)$ free from the influence of body mass. Intra- or inter-group comparisons can be made using a t test or analysis of variance (Winter, 1992), albeit on the log scale.

The advantage of allometry is that other confounding variables can be easily incorporated in the allometric model as further covariates and increase the sensitivity of the allometric model. Nevill & Holder (1995) demonstrated this by including further covariates (*age* & *age*^{2}) into their allometric model to account for the exponential decline in $\dot{V}O_{2\,max}$ with increasing age.

Another advantage of allometry is that logarithmic transformations linearise the model. This transformation makes the assumption that on the original scale the error is multiplicative and not additive (Scholl, 1948), allowing for the heteroscedasticity often associated with raw physiological data, such as $\dot{V}O_2$ (Nevill *et al.* 1992). However, as clearly demonstrated by Welsman *et al.* (1996), the distribution of raw and log transformed data should be always checked.

From a theoretical and empirical viewpoint, the numerical value of the exponent (*b*) in the allometric equation estimating the nature of the relationship between $\dot{V}O_{2\,max}$ and body size is the subject of some debate. Historically, such a relationship is based on the rules of geometric similarity.

The rules of geometric similarity have been known since Euclid's time (300 B.C.). Later, Archimedes (287 - 212 B.C.) established that '...similar geometrical bodies with corresponding surfaces increase as the square and the volumes increase as the cube of linear dimensions' (Günther, 1975, *p*. 660). More than 300 years ago, Galileo (1564 - 1642) not only discussed geometrical similarity of animals of different sizes but also introduced dynamical aspects, particularly regarding the strength of supporting structures, such as bones.

> 'Galileo understood the simple consequence of increased body size, that, as a linear dimension is increased, the mass of a similarly shaped animal increases by the cube of the linear dimension, and that strength of the supporting structures must be correspondingly increased. It is a minor matter that Galileo, judging from his drawing of a scaled bone, made an arithmetical mistake and increased its diameter by the square of its length, instead of the 1.5 power' (Pedley, 1977, *p*. 3)

To illustrate his point on geometrical similarity in animals, Galileo pointed out that 'A dog could probably carry two of three such dogs upon his back; but I believe that a horse could not carry even one of his own size' (Günther, 1975, *p*. 660).

Observers of living organisms since Galileo have recognised that metabolic surface areas, rather than body volumes must somehow limit activities. In their 1839 published assessment by the l'académie Royale de Médicine (see Appendix 2·1 for translation), Sarrus and Rameaux stated that heat loss of an animal must somehow be related to their 'unrestricted-surface', so were the first to propose the 'surface-law'. This theory was finally supported by empirical evidence published by Rubner in 1883. He observed that heat production rate divided by total body surface area was nearly constant in dogs of various sizes, and proposed the explanation that metabolically produced heat was limited by an animal's ability to lose heat, and thus by body surface area (*cited* Taylor, Schmidt-Nielsen and Raab, 1970).

Table 2·2: Radius, surface area and volume in spheres.

Radius (cm)	Surface area (cm^2)	Volume (cm^3)	*ln*(Surface area) *ln*(cm^2)	*ln*(Volume) *ln*(cm^3)
0.5	3.1	0.5	1.145	-0.647
1	12.6	4.2	2.531	1.432
2	50.3	33.5	3.917	3.512
3	113.1	113.1	4.728	4.728
4	201.1	268.1	5.304	5.591
5	314.2	523.6	5.750	6.261

This 'surface-law' predicts that '...as the volume of a body is increased, its surface does not increase in the same proportion (i.e. not linearly related), but only in proportion to the two-thirds power of the volume...' (Schmidt-Nielson, 1984, *p.* 13). Such proportionality between surface area and volume is better visualised using a three-dimensional object such as a sphere. As shown in table 2·2 and illustrated in Figure 2·2, calculating the surface area ($4\pi r^2$) and volume ($4/3\pi r^3$) of a sphere for a given radius (r) and plotting them clearly demonstrates that the surface area increases less rapidly that its volume.

Following the procedures discussed above, the relationship between surface and volume can be investigated further by plotting *ln*(surface area) area with *ln*(volume). As illustrated in Figure 2·3, the relationship is now represented as a straight line with slope, b, of 0.667 or 2/3, which is the proportionality coefficient between surface area and volume. This exponent (b) expresses a general relationship

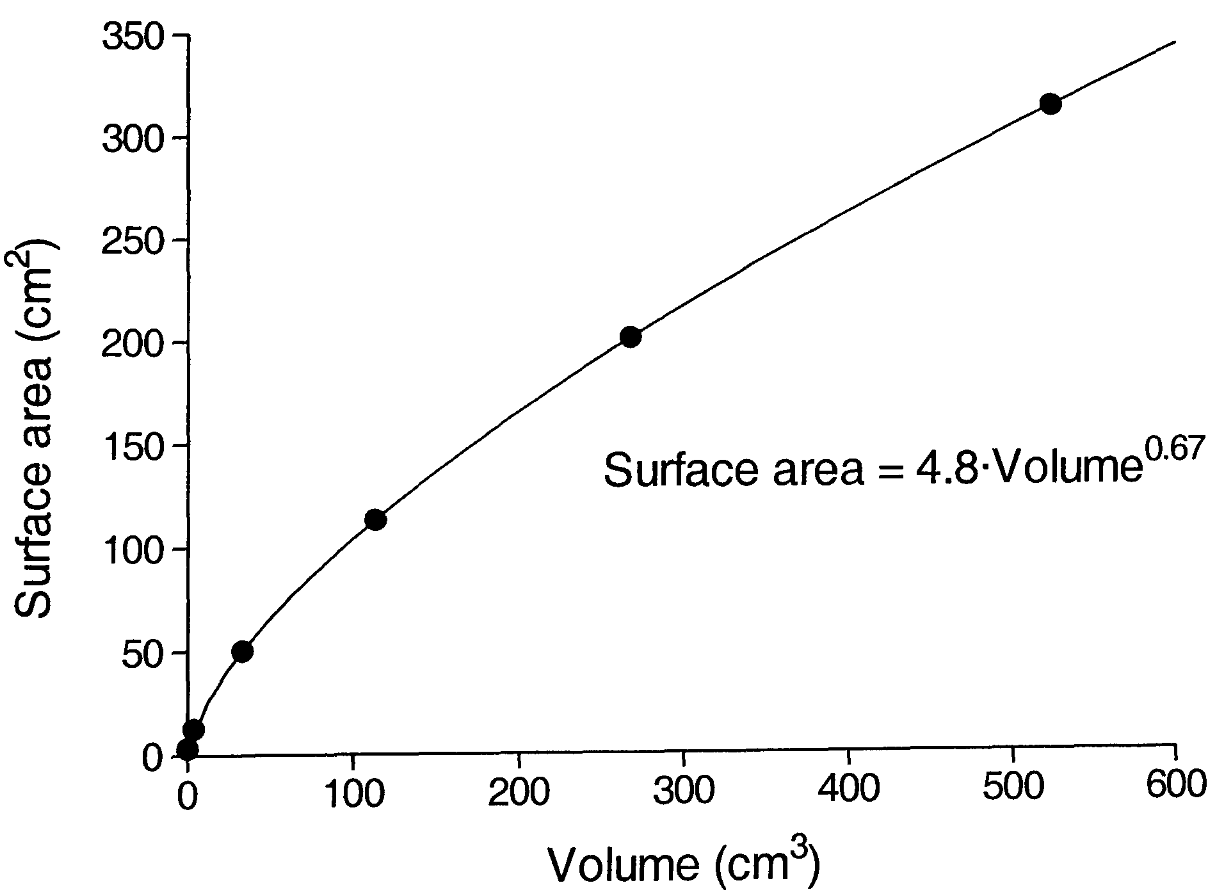

Figure 2·2: The relationship between surface area and volume in spheres.

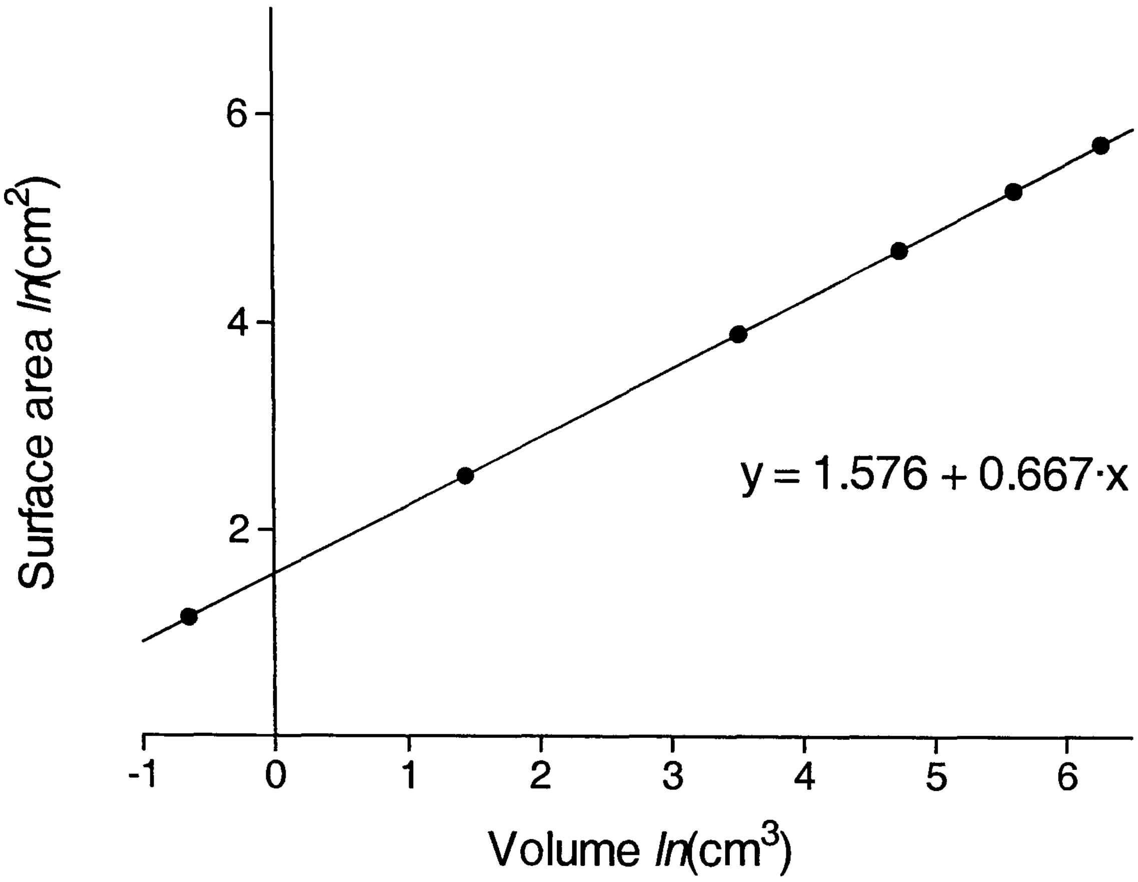

Figure 2·3: The relationship between *ln*(surface area) and *ln*(volume) in spheres.

of surface area to volume in all isometrically similar three-dimensional objects and provides the basis for the 'surface-law'. The exponentiated value of the intercept, *a*, is 4.84 and represents the '...specific surface of a unit volume....often called the Meeh constant' (Kleiber, 1950, *p*. 419). It is termed the constant multiplier in an allometric model.

Although the 'surface-law' appeared theoretically sound, it has not been born out too well in practice. Higher than expected body size scaling exponents have plagued the literature for allometric modelling in the biological sciences (Weibel, 2002) and more recently in human physiology (Nevill, 1994; Batterham *et al.*, 1999). It started with Max Kleiber in his 1932 publication "Body Size and Metabolism" (Kleiber, 1932), describing his investigation into metabolic rate in a wide variety of species that ranged in size from rats to cattle (4000-fold difference in body size) (Schimdt- Nielsen, 1984). Kleiber found that the best fit for his data was a body mass exponent of 0.74 and not 0.67 as predicted from the 'surface-law'. Since then a number of studies have published data supporting Kleiber's finding (for example, Benedict, 1938; Brody, 1945; Tenney & Remmers, 1963) and a body mass exponent of 0.75, relating metabolism to body size, has been widely accepted in the biological sciences. Although Heusner (1982) dismissed this as a statistical artefact, attempts have been made to provide theoretical support for this value; such as McMahon's theory of elastic similarity (1973). The biological justification for the 0.75 body mass exponent has yet to be confirmed (Heusner, 1982).

More recently in the field of human physiology, based on the findings of Alexander, Jayes, Maloiy and Wathuta (1981), Nevill (1994) suggested that these higher than expected exponents are attributable to the influence of disproportionate increases in muscle mass relative to body size. To allow for this influence Nevill (1994) suggested that stature could be incorporated into the allometric equation as a continuous covariate.

$$y = a(stature^{c})x^{b}$$

This had the effect of reducing the original body mass exponent of 0.81 to 0.67, exactly as predicted from the 'surface-law'. However, this approach was criticised by Batterham, Tolfrey and George (1997) who argued that the strong correlation between body mass and stature caused collinearity problems and the identification of a 2/3 body mass exponent '...may be a fortuitous statistical artefact' (*p*. 693). This disagreement has generated much lively debate, which continues.

Darveau, Suarez, Andrews and Hochachka (2002) have recently proposed a revolutionary theory that no single body size exponent exists between metabolic rate and body size. Moreover, they argue that the relationship between body size and metabolic rate changes between rest and exercise. During exercise O_2 supply to muscle is greatly increased and it is this accelerated process that changes the relationship. They proposed an integrated approach that takes into account all the important O_2 'delivery steps', which they feel, raise the body mass exponent higher than that found at rest. This new theory was recently reviewed by Weibel (2002) who concluded 'Whether Darveaus *et al.*'s model is the ultimate wisdom remains to be seen, but it does give the field of comparative integrative physiology a new thrust' (*p*. 132).

Regardless of the above theories, non-linear allometric modelling has been demonstrated to be a successful scaling technique. The principles underlying allometry are elementary and have been commonly applied in biology and zoology since the turn of this century (Thompson, 1917). In physiology, these principles are frequently overlooked even though there is an increasing body of evidence that suggests that current scaling techniques, ratio standards, are incorrect and misleading. This is exemplified by the contention about possible gender differences in maximal and sub-maximal oxygen consumption, much of which might simply be due to inappropriate scaling techniques. Applying this technique to different populations, the purpose of this study was to identify the most appropriate way to express values for maximal and sub-maximal oxygen consumption, and so allow meaningful comparison between men and women.

Chapter 3

REPRODUCIBILITY

The reliability of measurements, where possible, was assessed using test-retest reproducibility and interpreted using the methods recommended by Sale (1990) and Norton, Marfell-Jones, Whittingham, Kerr, Carter, Saddington and Gore (2000). All collection techniques were made following the guidelines laid down by The British Association of Sport and Exercise Sciences (Bird & Davidson, 1997; Hale, Armstrong, Hardman, Jakeman, Sharpe and Winter, 1988) and thoroughly practised before study data collection started.

REPRODUCIBILITY OF MEASURES

Anthropometry

Taking consideration of the possibility of error associated with measurement of body composition, the reliability and reproducibility of anthropometric variables were assessed using an inter- and intra-experimenter test-retest design. Two experimenters (myself and one experienced) made measurements of body mass, stature and four skin-folds on 16 physical education students (8 male, 8 female), following the guidelines recommended by Weiner and Lourie (1981). Measurements were repeated on the same participants seven days later at the same time of day.

Following the procedures described by Durnin and Womersley (1974) and the formula of Siri (1961), percentage body fat was estimated from the sum of the four skin-fold measurements. Data were collated and are summarized in Table 3·1, see Appendix 3·1 for individual data. Analysis of covariance (ANCOVA) revealed no significant evidence of a gender interaction ($p < 0.01$) for any measure so confirming that the test-retest data from the men and women could be combined.

Not surprisingly, the measurement of stature and mass showed good reproducibility. Technical error of measurement (see Norton *et al.*, 2000) for myself was 0.6 and 0.2 %, respectively, which compared well with 0.6 and 0.1 % of the more experienced experimenter (Prof. Winter). The value of 0.6 % reported by both experimenters for BM is nearly identical to the value of 0.62 % reported by Morgan, Martin, Krahenbuhl and Baldini (1991). Considering the reported variability in skin-fold measurements (Clarys, Martin, Drinkwater & Marfell-Jones, 1987), the methods error of 5.1 and 3.6 % for sum of skin-folds (mm) and body-fat (%) for myself were deemed satisfactory. Although a little higher, my reproducibility compared well with that of the more experienced experimenter (4.3 & 2.7 %, respectively) and the maximum measurement tolerance for skin-fold and body fat estimation of 5 %, recommended by Norton *et al.* (2000).

Table 3·1: Between and within-investigator test-retest reproducibility of mass, stature, skinfolds and body fat percentage.

	n	Test 1 Mean	Test 1 SD	Test 2 Mean	Test 2 SD	r	t	SDD	ME	ME%	L of A
Investigator: Patrick Johnson											
Mass (kg)	16	67.4	10.4	67.6	10.6	0.999	-1.08	0.53	0.4	0.6	-0.5, 0.1
Stature (cm)	16	173.1	8.1	173.4	8.0	0.997	-0.92	0.60	0.0	0.2	-0.5, 0.1
ΣSkinfolds (mm)	16	42.3	13.4	41.9	13.8	0.975	0.46	3.04	2.1	5.1	-1.3, 2.0
Bodyfat (%)	16	20.2	7.1	20.0	7.2	0.990	0.71	1.02	0.7	3.6	-0.4, 0.7
Investigator: Professor Edward Winter											
Mass (kg)	16	67.3	10.4	67.6	10.6	0.999	-1.17	0.54	0.4	0.6	-0.5, 0.1
Stature (cm)	16	172.8	7.9	172.8	8.1	0.997	0.21	0.00	0.0	0.0	-0.3, 0.3
ΣSkinfolds (mm)	16	42.3	14.8	43.2	15.8	0.988	-1.08	2.62	1.9	4.3	-2.3, 0.5
Bodyfat (%)	16	20.1	7.5	20.3	7.8	0.996	-0.98	0.77	0.5	2.7	-0.6, 0.2

ME = Technical error of measurement, SDD = Standard deviation of the difference, L of A = Limits of agreement

Source: Appendix 3·1

Table 3·2: Test-retest reproducibility of maximal oxygen uptake and related measures.

		Test 1		Test 2							
	n	Mean	SD	Mean	SD	*r*	*t*	SDD	ME	ME%	L of A
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	6	4.30	0.40	4.41	0.42	0.957	-2.22	0.12	0.09	2.0	-0.24, 0.02
RER	6	1.08	0.05	1.08	0.03	0.870	-0.13	0.03	0.02	2.1	-0.013, 0.032
Max HR ($b \cdot min^{-1}$)	6	192	8	191	11	0.943	0.42	3.88	2.74	1.4	-3.41, 4.74
Blood lactate ($mmol \cdot l^{-1}$)	6	8.7	2.0	8.5	1.8	0.775	0.26	1.28	0.90	10.5	-1.21, 1.48
Run time (secs)	6	607	84	616	98	0.950	-0.70	32.2	22.7	3.7	-42.9, 24.6

ME = Technical error of measurement, SDD = Standard deviation of the difference, L of A = Limits of agreement
Source: Appendix 3·2

Maximal oxygen uptake

Reproducibility of $\dot{V}O_{2\,max}$, and associated criteria for assessing whether $\dot{V}O_{2\,max}$ was achieved, were assessed on six physical education students using a test-retest

design (Sale, 1991). Maximal oxygen uptake was determined during a continuous incremental treadmill run to volitional exhaustion; more details on procedures are provided in the methods of each study. Measurement was repeated on the same participants seven days later at the same time of day to minimise circadian and other similarly induced variations in performance. Summary of the data collected is presented in Table 3·2, and collated in Appendix 3·2.

Technical error of measurement of 2.0 % for $\dot{V}O_{2\,max}$ compared favourably with values reported by Svedenhag and Sjödin (1994), Howley, Bassett and Welch (1995) and Katch, Sady and Freedson (1982) of 3.3, 4.0 and 5.6 %, respectively. In addition, method error for respiratory exchange ratio (RER) (2.1 %), maximum heart rate (1.4 %) and run time (3.7 %) indicated good reproducibility and compared well with similar values reported by Brown, Swaine and Winter (1996) of 2.4, 1.1 and 1.7 %, respectively. Method error for blood lactate was slightly higher at 10.5 % but, this compared well with the value of 9.6 % reported by Brown *et al.* (1996).

Sub-maximal oxygen uptake

Reproducibility of sub-maximal $\dot{V}O_2$ was assessed using a repeated trials protocol (Sale, 1991). Sub-maximal $\dot{V}O_2$ at four treadmill running speeds (2.68, 3.13, 3.58 & 4.05 $m \cdot s^{-1}$) was determined on one runner on six separate days at the same time of day. Summary of the data collected is presented in Table 3·3.

The coefficient of variation (CV) of between 1.3 and 3.0 % for sub-maximal $\dot{V}O_2$ compared well with values reported by Morgan *et al.* (1991) of 1.32 % (range = 0.30 - 4.40). Williams, Krahenbuhl and Morgan (1991), who assessed daily variation in running economy at similar running speeds (2.68, 3.13 & 3.58 $m{\cdot}s^{-1}$), also found similar CV values of 3.1, 2.6 and 2.5 %, respectively, concluding that '...running economy appears to be a stable physiological measure...' (*p*. 944).

Table 3·3: Oxygen uptake and repeated measures coefficient of reproducibility (n = 6) at four sub-maximal running speeds.

	Oxygen uptake ($l{\cdot}min^{-1}$)			
Test	2.68 $m{\cdot}s^{-1}$	3.13 $m{\cdot}s^{-1}$	3.58 $m{\cdot}s^{-1}$	4.02 $m{\cdot}s^{-1}$
1	2.07	2.51	2.82	3.41
2	2.07	2.47	2.90	3.40
3	2.08	2.57	3.02	3.48
4	2.01	2.46	2.88	3.36
5	2.16	2.46	3.01	3.42
Mean	2.08	2.49	2.93	3.41
SD	0.05	0.05	0.09	0.04
CV (%)	2.58	1.89	2.96	1.27

INSTRUMENT RELIABILITY AND CALIBRATION

Gas analysers

A two-point calibration was performed on the O_2 and CO_2 analysers immediately before each maximal and sub-maximal $\dot{V}O_2$ testing session and verified immediately after. The analysers were calibrated with nitrogen gas (zero calibration) and an accurately measured span gas mixture (British Oxygen Company). Maximum allowable drift was 0.04 % for O_2 and 0.06 % for CO_2, both of which were within manufacturer tolerances (Servomex UK Ltd, Sussex).

Dry gas meter

Using a repeated trials (n = 5) procedure (Sale, 1991), the dry gas meter readings were checked before, during and at the end of all testing over a working range of values (14 - 140 litres). Maximum error found was 0.7 %, well within manufacturer's tolerance, and deemed acceptable. Example dry gas meter calibration report is provided in Appendix 3·3.

Treadmill

Running speeds indicated by the treadmill were checked during and after completion of all testing. The measured speeds were used in preference to the indicated speeds throughout this study. Indicated speeds were also checked using three runners of different size, concluding that there was little or no difference in the treadmill speed due to the mass of the participant (see Appendix 3·4).

Skin-fold calipers, stadiometer and massing scales

Using a repeated trials procedure, skin-fold calipers were checked in line with the guidelines laid down by Weiner and Lourie (1984). Stadiometer and weighing scales were regularly calibrated with a known reference.

Chapter 4

STUDY 1

Modelling of maximal oxygen uptake in male and female distance runners.

INTRODUCTION

Important to the success in endurance sporting events is the maximum rate at which an athlete can extract, transport and use oxygen ($\dot{V}O_{2\,max}$). Women endurance athletes tend to exhibit a lower $\dot{V}O_{2\,max}$ per given unit of body mass than their male counterparts and this difference has been attributed in some part to their inferior endurance performance. As previously discussed, an influence on $\dot{V}O_{2\,max}$ is simply the size of the body as a whole or of its exercising segments, so to explore the qualitative characteristics of the tissues meaningfully differences in size have to be partitioned out.

Conventionally, because men tend to be bigger than women, this difference in body size is said to have been removed by simply dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass (BM) to produce a per-mass ratio standard ($ml \cdot kg^{-1} \cdot min^{-1}$). However, unless exceptional circumstances are satisfied (Tanner, 1949) the use of these ratio per-body mass standards fail to remove the influence of body size and has been shown to distort the data leading to possible misinterpretation (Bergh *et al.*, 1991; Nevill *et al.*, 1992; Vanderburgh & Mahar, 1995; Welsman *et al.*, 1996). This is especially the case when differences in body size are marked (Winter, 1992), such as comparisons between men and women.

Schmidt-Nielsen (1984) clearly demonstrated that not all relationships are linear and in the field of biology and zoology there is a long established tradition of the use of allometry to investigate such relationships (Huxley, 1932; Thompson, 1917). Allometry scales a physiological variable (y) in relation to body size (x) through the equation:

$$y = a \cdot x^b$$

where a is a constant multiplier and b the exponent. With the use of a logarithmic transformation and least squares regression these parameters can be estimated with the value a representing a ratio, known as a power function ratio (Kleiber, 1950), which expresses y independent of x $\left(\frac{y}{x^b}\right)$. Introducing $\dot{V}O_{2\,max}$ and body mass into the above equation the following model was proposed by Nevill *et al.* (1992):

$$\dot{V}O_2 max = a \cdot BM^b$$

Values for $\dot{V}O_{2\,max}$ can now be expressed as power function ratios (a) that are free from the influence of body mass $\left(\frac{\dot{V}O_2 max}{BM^b}\right)$. Where allometry has been used to adjust $\dot{V}O_{2\,max}$ for differences in body mass two exponents have been propounded: 0.67, derived from the surface law (Sarrus & Rameaux, 1839), and 0.75, from the theory of elasticity (McMahon, 1973).

In gender comparisons of $\dot{V}O_{2\,max}$ not only is it important to select the most appropriate scaling method, the choice of an appropriate measure of size is also paramount. Women tend to have a greater percentage of body fat than men and hence a reduced proportion of lean body mass, in particular muscle. Muscle is the greatest consumer of O_2 during maximal aerobic exercise. Although a reliable measure, indiscriminate use of body mass fails to account for the confounding influence of body fat and results in a larger difference in $\dot{V}O_{2\,max}$ being reported between men and women. Free from this influence of body fat is the estimated measure fat free mass (FFM), termed a 'mathematical adiposectomy' (body mass –

fat mass) by Gitin *et al.* (1974), which should be a preferred alternative to body mass.

Therefore the purpose of this study was to investigate the relationship between $\dot{V}O_{2\,max}$ and body size (BM & FFM) in male and female distance runners and to explore the most appropriate scaling method to remove this influence and so make meaningful gender comparison.

METHODS

Participants

Thirty-four middle- and long-distance runners (17 male, 17 female) were recruited from running clubs in the South East of England. Participants were selected using the following criteria:

- age: between 16 - 35 years old
- experience: minimum of three years
- training status: currently in full training and free from injury

All participants were given written details of the procedures to be used and they provided written informed consent (see Appendix 4·1). To help ensure participants' motivation for the $\dot{V}O_{2\,max}$ assessment, the tests were presented as a fitness assessment with reports produced for each participant.

General procedures

All testing took place in the Physiology of Exercise Laboratories at De Montfort University, Bedford, and conducted in accordance with the guidelines laid down by the British Association of Sports Sciences (Bird & Davidson, 1997; Hale, Armstrong, Hardman, Jakeman, Sharp & Winter, 1988). Further to an initial visit to habituate the participants to treadmill running, expired air collection and other experimental procedures; participants' $\dot{V}O_{2\,max}$ was assessed via the treadmill. All tests took place at times when the participants would normally have trained and participants were instructed to have refrained from exercise for at least 24 hours (> 48 hours hard training) and be at least 2 hours post absorptive.

Ambient laboratory temperature was always 20°C (± 2), controlled by Mitsubishi (Mr Slim) air conditioning unit. Humidity, although not controlled, ranged from 17 - 57%.

The procedures and equipment used were similar to those used in pilot and reproducibility tests carried out prior to testing, see Chapter 3, on reproducibility of methods and calibration, for more details.

Mass and stature

Measurement of mass and stature were made in accordance with the guidelines laid down by Lohman, Roche and Martorell (1988). Stature was measured to the nearest 0.001 m, using a Holtain Harpenden stadiometer, and body mass measured to the nearest 0.05 kg, using Seca (model 713) beam scales, immediately prior to testing.

Body composition

Following the guidelines set by Weiner and Laurie (1981), skin-fold measurements were made using Holtain calipers on the left side of the body over the biceps, triceps, sub-scapula and suprailiac. Three measurements were made at each site, with the mean of the closest two values being used. Taking the logarithm of the sum of the skin-fold measurements, body density was estimated using the equations described by Durnin and Womersley (1974) and percentage body fat calculated from the formula of Siri (1961):

$$\%\text{fat} = \left(\frac{4.95}{\text{Density}} - 4.95 \right) \times 100$$

Fat mass and fat-free mass (FFM) were then calculated. To minimise the error normally associated with this measurement, inter and intra-investigator reproducibility had been assessed prior to data collection (see Chapter 3) and the same callipers were always used which had been calibrated with weights following the instructions given by Weiner and Lourie (1981).

Maximal oxygen uptake

Maximal oxygen uptake was determined by the open circuit method during a continuous incremental treadmill run to volitional exhaustion (Hale *et al*, 1988; Lange-Anderson, Shephard, Denolin, Varnauskas & Masironi, 1971). After a five-minute warm-up and flushing out of the connecting tubes with the participant's expirate, the test was started with a constant treadmill (Powerjog, M30) speed and 0 % gradient. Every three minutes the gradient rose by 2.5 %, and the test continued until the participant reached volitional exhaustion. At a suitable point expired air collection commenced, in sequence with pulmonary cycles, for time intervals approximating to 60 seconds, measured accurately to the nearest one-hundredth second by an electronic bag-timing system and BBC Micro (8000) computer and software. The expired air was collected, via a low-resistance Salford breathing valve and Falconia tubing, in 150 litre Douglas bags with Rudolph 2700 two way valves. The expirate was condensed, and O_2 and CO_2 fractions determined using a Servomex 1490 infrared (CO_2) analyser and a Servomex 1100 paramagnetic oxygen transducer. Expirate volume was determined by first drawing the expirate through a drying agent (silica crystals) and then measured by a Harvard dry gas meter. Temperature of expirate was measured from the exit area of the gas meter.

Prior to testing 3 electrodes were attached to the participant in a modified V_5 formation and connected to an ECG to monitor heart rate. Finger prick blood samples were taken from the participant immediately prior to and 4½ minutes post exercise and analysed for blood lactate concentration using a YSI analyser (2300 stat plus).

Maximal oxygen uptake was considered maximal provided four of the following six criteria were achieved:

- Plateau in $\dot{V}O_2$ within 2 $ml \cdot kg^{-1} \cdot min^{-1}$ and/or 5%
- Respiratory exchange value of 1.10 or greater
- Peak recorded heart rate ≥ 90 % of age predicted maximum (220 - age)
- Post exercise blood lactate concentration ≥ 8 $mmol \cdot l^{-1}$
- Run time of between 8 - 15 minutes
- Subjective appraisal of fatigue

Analyses

All analysis were made using SPSS version 9 (SPSS Inc., Chicago, IL). Descriptive statistics were performed on the summary data and preliminary analyses of the relationship between body mass and fat-free mass with $\dot{V}O_{2\,max}$ were made using graph plots and bivariate correlation. The following models were used to express $\dot{V}O_{2\,max}$:

1. Ratio standard, constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass and expressed in $ml \cdot BM^{-1} \cdot min^{-1}$. Gender comparison made using independent *t* test.
2. Power function ratio using 0.67 as the body mass exponent (PFR67), constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass raised to the power 0.67 ($BM^{0.67}$)

and expressed in ml·BM$^{-0.67}$·min^{-1}. Again gender comparison made using independent t test.

3. Power function ratio using 0.75 as the body mass exponent (PFR75), constructed by dividing $\dot{V}O_{2\,max}$ (ml·min^{-1}) by body mass raised to the power 0.75 (BM$^{0.75}$) and expressed in ml·BM$^{-0.75}$·min^{-1}. Gender comparison made using independent t test.

4. Body mass allometric model. The influence of body mass on $\dot{V}O_{2\,max}$ was investigated using the allometric model proposed by Nevill & Holder (1994).

$$\dot{V}O_{2\,max} = a \cdot \mathrm{BM}^{b} + \in$$

The influence of sex was also investigated by incorporating a dummy *sex* variable (coded '0' for women and '1' for men), so producing an expression of the form:

$$\dot{V}O_{2\,max} = \mathrm{BM}^{b} \cdot \exp(a + c \cdot \mathrm{sex}) \cdot \in$$

where $\in$ represents a random multiplicative error term. The model was linearised by taking the natural logarithm (*ln*) of $\dot{V}O_{2\,max}$ and body mass. Hence:

$$ln\ \dot{V}O_{2\,max} = b \cdot ln\mathrm{BM} + a + c \cdot \mathrm{sex} + ln\in$$

To confirm that men and women could be compared using the same body mass scaling exponent, the homogeneity of the body mass coefficient was first verified by including a $sex \times ln$BM variable into the linearised model to check for any interaction. Following this verification, coefficients a, b and c were identified using multiple regression. Power function values were then constructed by dividing $\dot{V}O_{2\,max}$ (ml·min^{-1}) by body mass raised to the identified exponent (BM^{b}) and expressed in ml·BM^{-b}·min^{-1}.

5. Fat free mass ratio standard, constructed by dividing $\dot{V}O_{2\,max}$ (ml·min^{-1}) by fat free mass and expressed in ml·FFM^{-1}·min^{-1}. Gender comparison made using independent *t* test.

6. Fat free mass allometric model. Similar to model **4** but replacing body mass with fat free mass creating a linearised model of the form:

$$ln\ \dot{V}O_{2\,max} = b \cdot ln\mathrm{FFM} + a + c \cdot \mathrm{sex} + ln\epsilon$$

Homogeneity of the male and female fat free mass coefficients was first verified by including a *sex* × *ln*FFM variable into the model to check for any interaction. Following this verification, coefficients *a*, *b* and *c* were identified using multiple regression. Power function values were then constructed by dividing $\dot{V}O_{2\,max}$ (ml·min^{-1}) by fat free mass raised to the identified exponent (FFM^{b}) and expressed in ml·FFM^{-b}·min^{-1}.

To check the ability of each model to render $\dot{V}O_{2\,max}$ free from the influence of size, the constructed values from each model were correlated with either body mass or fat free mass.

Model diagnostics

For both allometric models (BM & FFM) the Kolmogorov-Smirnov test was used to check that the residuals about regression were normally distributed and the absolute residuals from the logged model (BM or FFM) were correlated with *ln*BM or *ln*FFM to check that the error structure of the data had been correctly treated (heteroscedasticity). Level of significance was set at $p < 0.05$.

RESULTS

Descriptive and recruitment criteria data both for men and women were summarised and presented in Table 4·1, see Appendix 4·2 for individual data. There were no gender differences in age and training experience ($p = 0.914$ & 0.468, respectively) indicating similar groups in terms of recruitment criteria. Not surprisingly, the men were heavier, taller and had less body fat than the women and had a higher absolute $\dot{V}O_{2\,max}$ ($p < 0.001$).

As expected, a positive relationship between $\dot{V}O_{2\,max}$ with body mass is clearly evident in Figure 4·1 with correlation coefficients of 0.787 and 0.854 for the men and women respectively ($p < 0.001$). A similar relationship is evident between $\dot{V}O_{2\,max}$ and fat free mass (R = 0.931 & 0.787, $p < 0.001$, respectively), as illustrated in Figure 4·2.

Table 4·1: Summary data for men and women (mean ± SD).

	Men (n = 17)	Women (n = 17)	t	p
Age (years)	23.2 ± 4.5	23.6 ± 6.5	0.11	0.914
Experience (years)	7.1 ± 4.8	8.2 ± 4.1	0.73	0.468
Stature (m)	1.80 ± 0.07	1.64 ± 0.07	6.52	< 0.001
Body mass (kg)	69.6 ± 5.2	55.8 ± 6.6	6.68	< 0.001
Body fat (%)	12.6 ± 3.5	22.6 ± 3.9	7.99	< 0.001
Fat free mass (kg)	60.9 ± 5.6	43.1 ± 4.6	10.09	< 0.001
$\dot{V}O_{2\,max}$ ($l\cdot min^{-1}$)	5.09 ± 0.60	3.31 ± 0.41	10.08	< 0.001

Source: Appendix 4·2

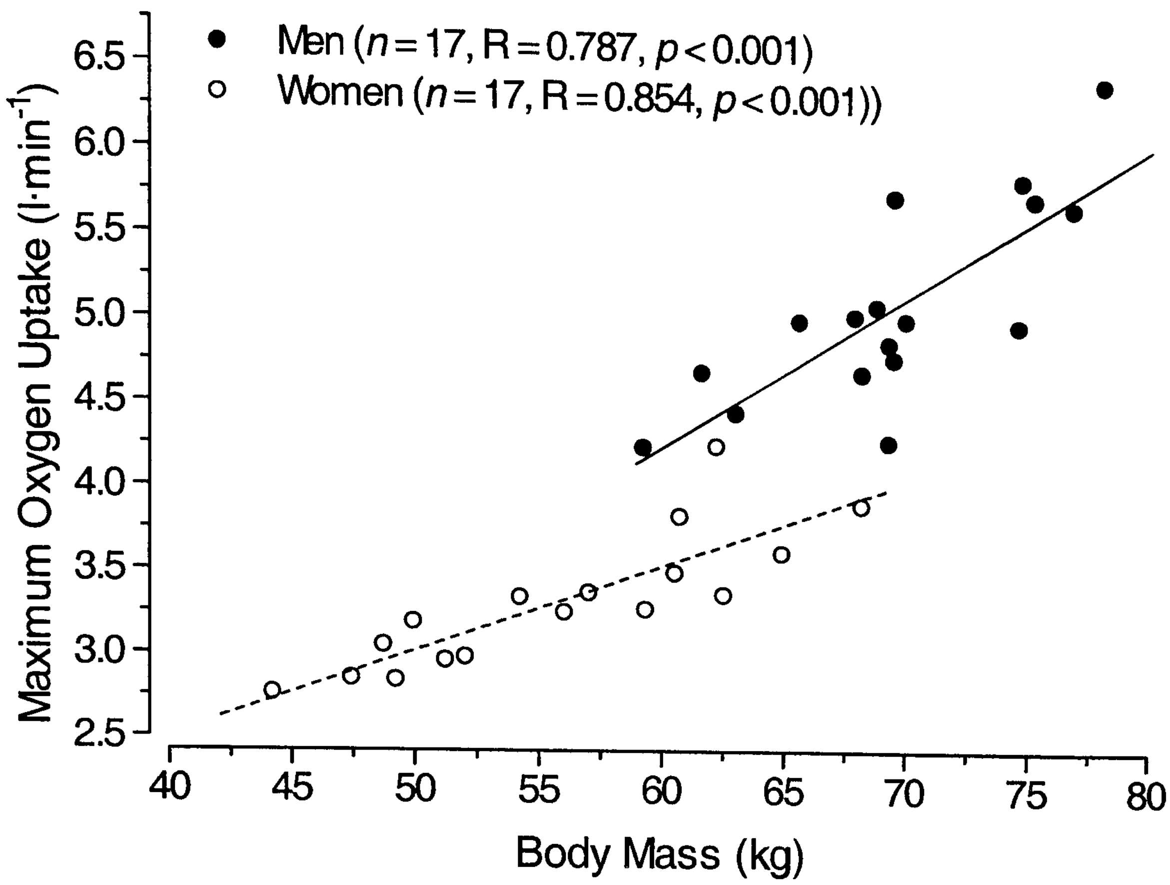

Figure 4·1: The relationship between maximal oxygen uptake and body mass in male and female distance runners.

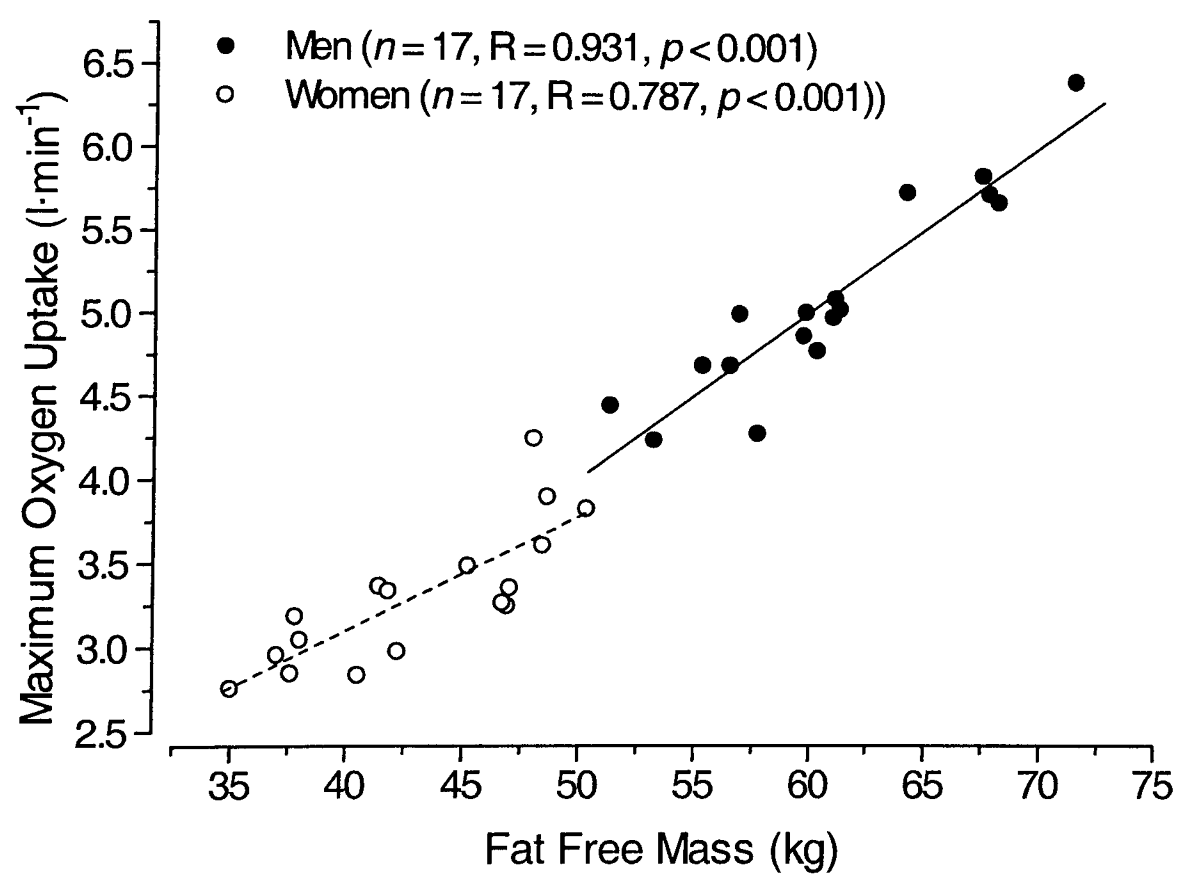

Figure 4·2: The relationship between maximal oxygen uptake and fat free mass in male and female distance runners.

1. Body mass ratio standards were calculated and summary presented in Table 4·2, see Appendix 4·3 for individual values. Values for $\dot{V}O_{2\,max}$ were, on average, 23 % higher in the men than the women (73.2 v 59.5 ml·BM^{-1}·min^{-1}, $p < 0.001$). As illustrated in Figure 4·3, when these values were correlated with body mass coefficients of 0.214 ($p = 0.410$) and -0.284 ($p = 0.270$), for the men and women respectively, indicate that in this sample the body mass ratio standard had successfully rendered $\dot{V}O_{2\,max}$ independent of body mass.
2. Power function ratios using a body mass exponent of 0.67 were calculated and summary presented in Table 4·2, see Appendix 4·3 for individual values. Values for $\dot{V}O_{2\,max}$ were, on average, 32 % higher in the men than the women (296 v 224 ml·BM$^{-0.67}$·min^{-1}, $p < 0.001$). When these values were correlated with body mass (Figure 4·4), coefficients of 0.500 ($p = 0.041$) and 0.352 ($p = 0.166$), for the men and women respectively, indicate that for the men using a body mass exponent of 0.67 is not appropriate and will have introduced bias into $\dot{V}O_{2\,max}$ scaled values.
3. Power function ratios using a body mass exponent of 0.75 were calculated (Appendix 4·3) and summary presented in Table 4·4. Values for $\dot{V}O_{2\,max}$ were, on average, 30 % higher in the men than the women (211 v 162 ml·BM$^{-0.75}$·min^{-1}, $p < 0.001$). When these values were correlated with body mass, coefficients of 0.441 (p=0.077) and 0.211 (p=0.416), for the men and women respectively, were identified indicating no relationship with body mass. Although an improvement on model **2**, the near significant correlation for the men would still suggest the body mass ratio standard a better model.

Table 4·2: Expression of maximal oxygen uptake.

	Maximal oxygen uptake						
	($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.75} \cdot min^{-1}$)	($ml \cdot BM^{-0.94} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-0.98} \cdot min^{-1}$)
Men (n = 17)							
Mean	5.09	73.2	296	211	94.8	83.6	91.9
SD	0.60	5.3	24	17	7.0	3.9	4.3
SEM	0.15	1.3	6	4	1.7	0.9	1.1
Women (n = 17)							
Mean	3.31	59.5	224	162	76.0	77.0	83.9
SD	0.41	3.7	15	10	4.6	5.5	6.0
SEM	0.10	0.9	4	2	1.1	1.3	1.4
Difference (%)	54	23	32	30	25	9	10
p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.036

Source: Appendix 4·3

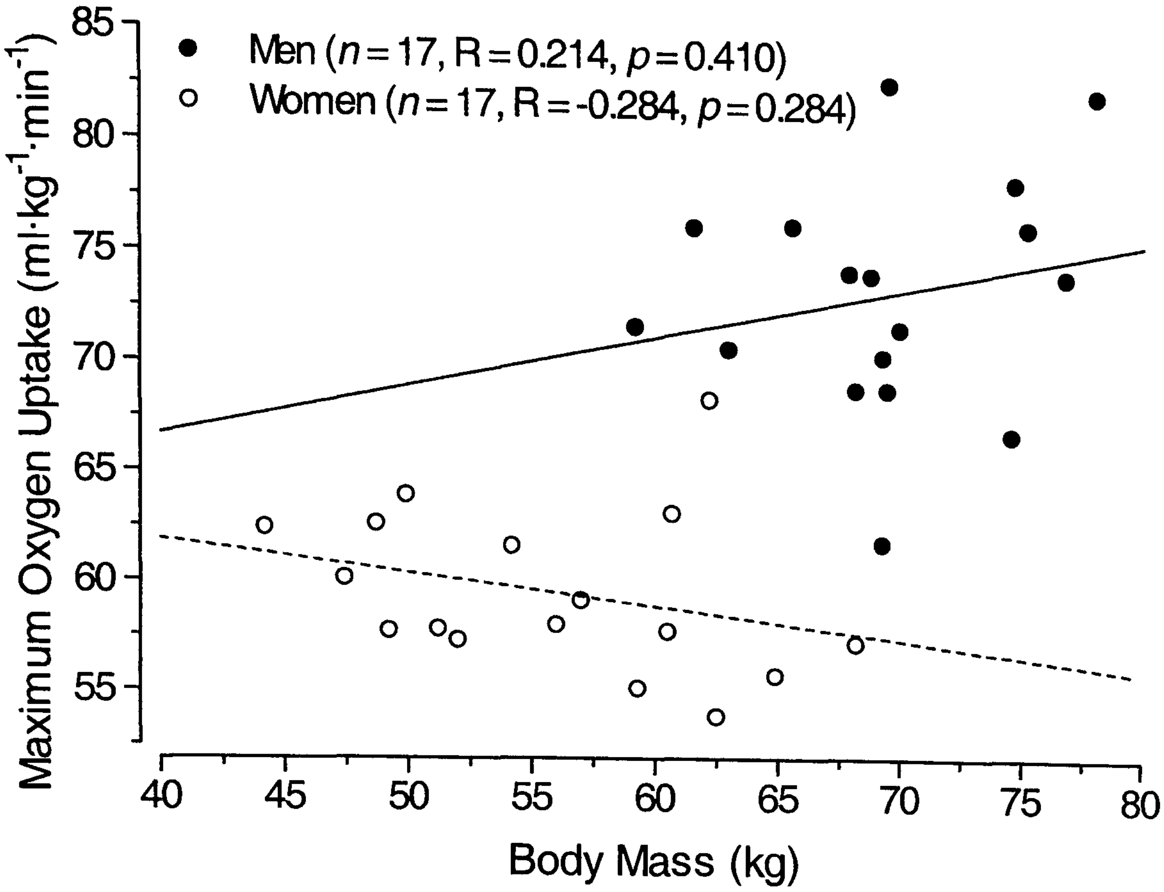

Figure 4·3: The relationship between maximal oxygen uptake, expressed as a ratio standard, and body mass in male and female distance runners.

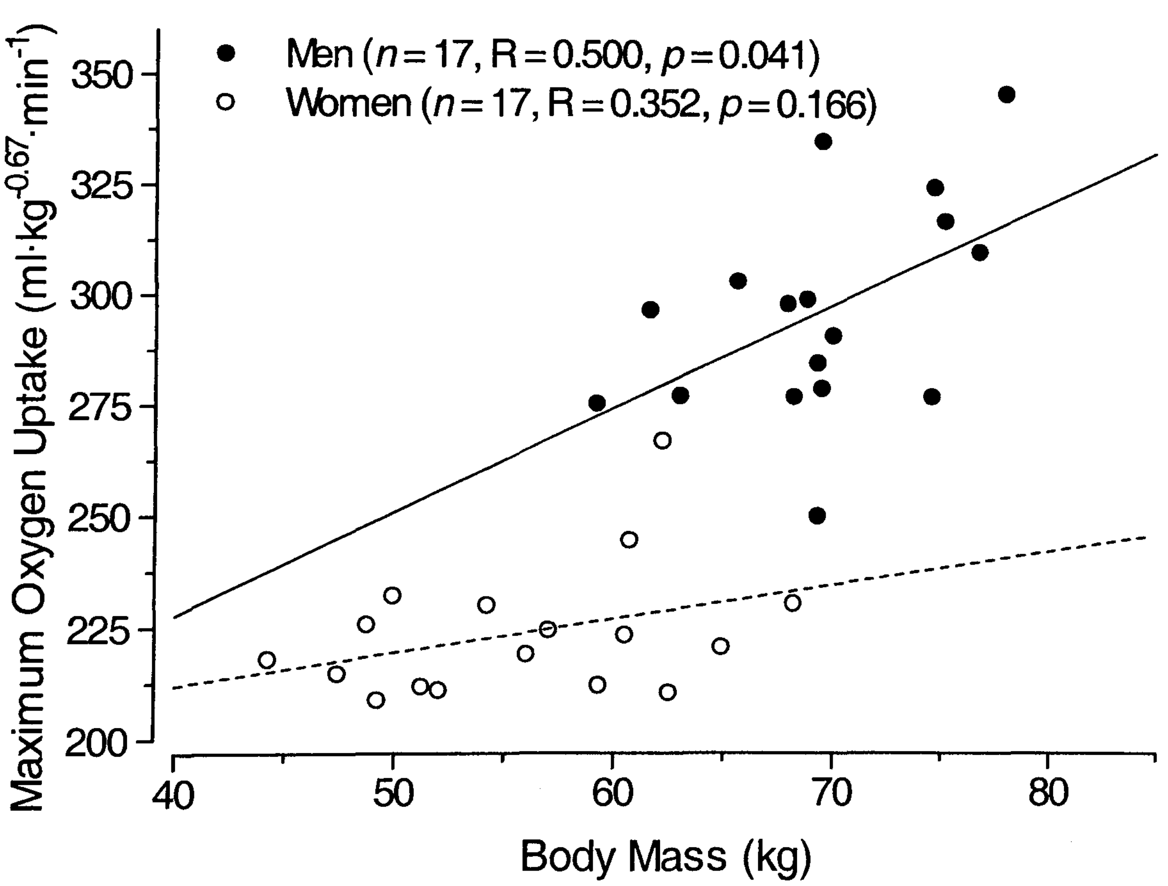

Figure 4·4: The relationship between maximal oxygen uptake, expressed as a power function ratio constructed using a body mass exponent of 0.67, with body mass in male and female distance runners.

4. There was no evidence of a *sex* × *ln*BM interaction ($t = 1.27, p = 0.215$) and thus the variable was removed from the model. This confirms the homogeneity of slopes between gender and justifies the analysis of the data using the same scaling body mass exponent. The model explained 92.8 % (R = 0.963, SEE = 0.0686) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*BM (0.939 ± 0.118), *sex* (0.219 ± 0.035) and intercept (-2.581 ± 0.473) were all significant ($p < 0.001$) and incorporated into the model, so producing the expression:

$$ln\,\dot{V}O_{2\,max} = 0.939 \cdot ln\text{BM} - 2.581 + 0.219 \cdot \text{sex} + \ln \in$$

By taking the antilogarithm on $ln\,\dot{V}O_{2\,max}$ and *ln*BM the following allometric model was derived:

$$\dot{V}O_{2\,max} = \text{BM}^{0.939} \cdot \exp(-2.581 + 0.219 \cdot \text{sex}) \cdot \in$$

Using the common body mass exponent, $\dot{V}O_{2\,max}$ values were calculated (Appendix 4·3) and summary presented in Table 4·2. Values for $\dot{V}O_{2\,max}$ were, on average, were 25 % higher ($e^{0.219}$) in the men than the women (94.8 v 76.0 $\text{ml} \cdot \text{BM}^{-0.94} \cdot \text{min}^{-1}$, $p < 0.001$). Correlating these values with body mass (see Figure 4·5), coefficients of 0.275 ($p = 0.286$) and -0.167 ($p = 0.522$), for the men and women respectively, were identified indicating that values were independent of body mass.

5. Fat free mass ratio standards were calculated (Appendix 4·3) and summary presented in Table 4·2. Values for $\dot{V}O_{2\,max}$ were, on average, 9 % higher in the men than the women (83.6 v 77.0 $\text{ml} \cdot \text{FFM}^{-1} \cdot \text{min}^{-1}$, $p < 0.001$). As illustrated in Figure 4·6, when these values were correlated with fat free mass coefficients of 0.342 ($p = 0.178$) and -0.210 ($p = 0.418$), for the men and women respectively,

indicate that in this sample the fat free mass ratio standard was appropriate and render $\dot{V}O_{2\,max}$ independent of fat free mass.

6. There was no evidence of a *sex* × *ln*FFM interaction ($t = 1.462, p = 0.154$) and thus the variable was removed from the model. The model explained 94.2 % (R = 0.971, SEE = 0.0613) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*FFM (0.977 ± 0.104) and intercept (-2.478 ± 0.392) were significant at $p < 0.001$ with *sex* (0.0919 ± 0.042) only just significant ($p =$ 0.036). Values were incorporated into the model, producing the expression:

$$ln\,\dot{V}O_{2\,max} = 0.977 \cdot ln\text{FFM} - 2.478 + 0.0919 \cdot \text{sex} + \ln\in$$

By taking the antilogarithm on $ln\,\dot{V}O_{2\,max}$ and *ln*FFM the following allometric model was derived:

$$\dot{V}O_{2\,max} = \text{FFM}^{0.977} \cdot \exp(-2.478 + 0.0919 \cdot \text{sex}) \cdot \in$$

Using the common fat free mass exponent (0.977), $\dot{V}O_{2\,max}$ values were calculated (Appendix 4·3) and summary presented in Table 4·2. Values for $\dot{V}O_{2\,max}$ were, on average, 10 % higher ($e^{0.0919}$) in the men than the women (91.9 v 83.9 $\text{ml} \cdot \text{FFM}^{-0.98} \cdot \text{min}^{-1}$, $p = 0.036$). Correlating these values with fat free mass (see Figure 4·7), coefficients of 0.383 ($p = 0.130$) and -0.174 ($p = 0.505$), for the men and women respectively, indicated that the values for $\dot{V}O_{2\,max}$ had been expressed independent of fat free mass.

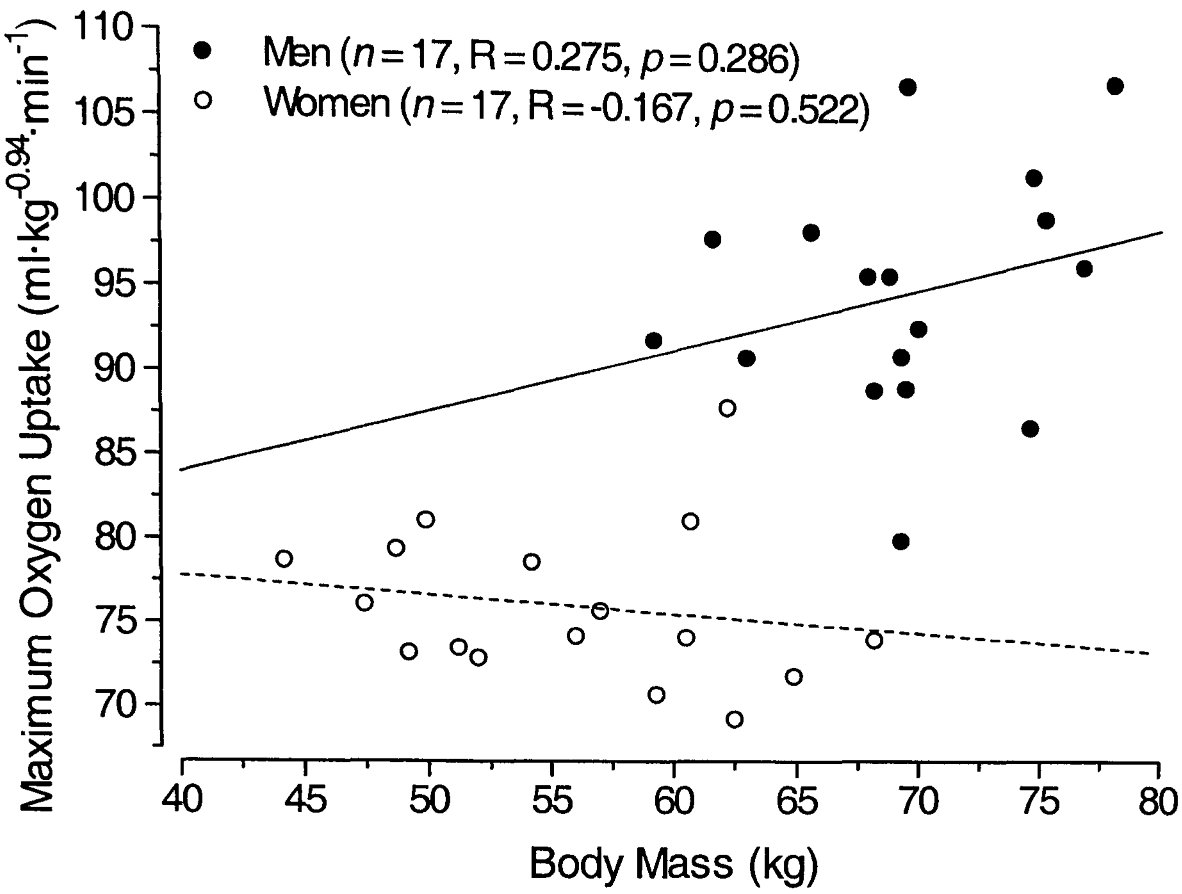

Figure 4·5: The relationship between maximal oxygen uptake, expressed as a power function ratio constructed using a common body mass exponent of 0.94, with body mass in male and female distance runners.

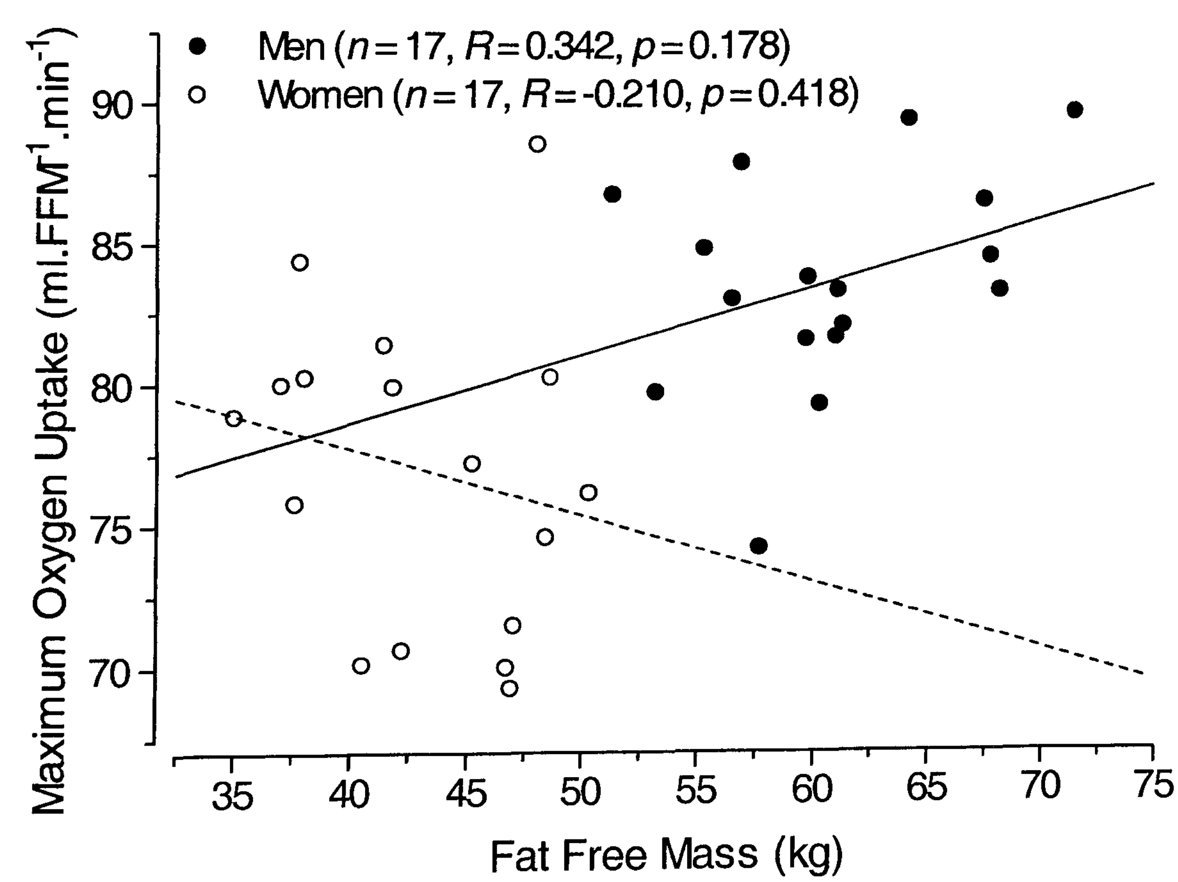

Figure 4·6: The relationship between maximal oxygen uptake, expressed as a ratio standard, and fat free mass in male and female distance runners.

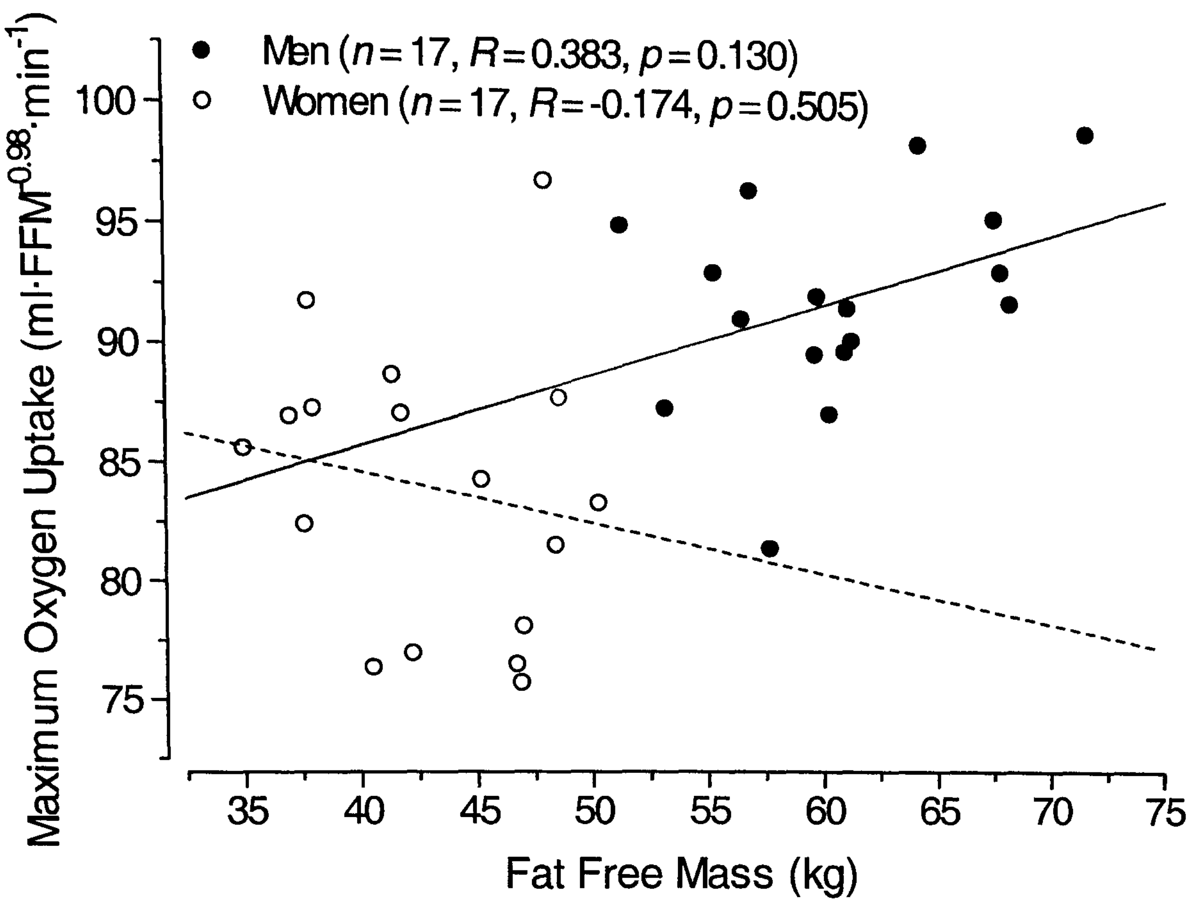

Figure 4·7: The relationship between maximal oxygen uptake, expressed as a power function ratio constructed using a common fat free mass exponent of 0.98, with fat free mass in male and female distance runners.

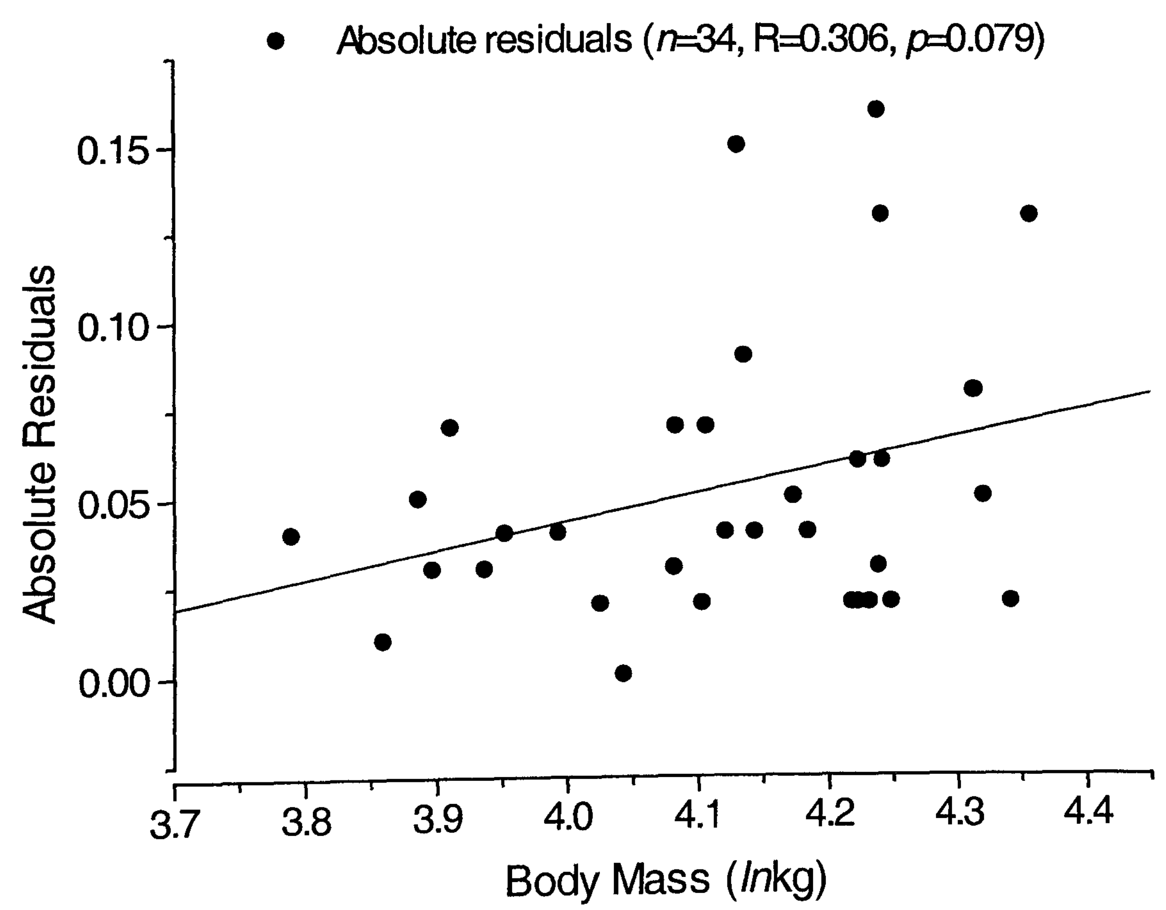

Figure 4·8: The relationship between the absolute residuals from the body mass allometric model and the natural logarithm of body mass.

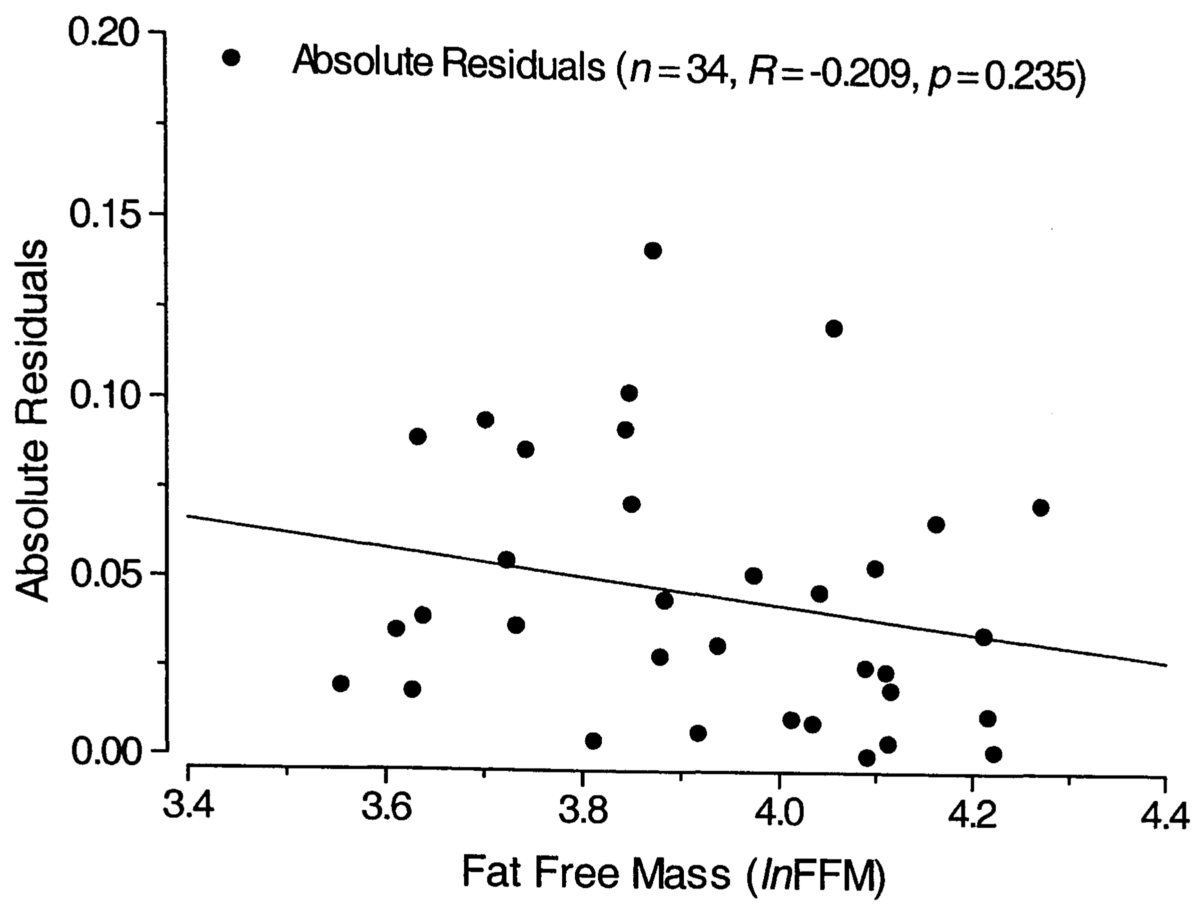

Figure 4·9: The relationship between the absolute residuals from the fat free mass allometric model and the natural logarithm of fat free mass.

Model diagnostics

The residuals from both allometric models (BM & FFM) were normally distributed ($p > 0.200$). As illustrated in Figure 4·9, there was no relationship between the absolute residuals from the fat free mass allometric model and *ln*FFM ($R = -0.209$, $p = 0.235$). This confirmed that the error was multiplicative and had been correctly treated by the logarithmic transformation. Similarly, no relationship (Figure 4·8) was found between the absolute residuals from the body mass allometric model and *ln*BM ($r = 0.315$, $p = 0.070$) but with a p value close to significance ($P < 0.05$) it is possible that the error had not been correctly treated.

DISCUSSION

There were no gender differences in recruitment criteria indicating a representative sample in terms of training status. Furthermore, $\dot{V}O_{2\,max}$ values (mean ± SD) for the men and women (73.2 ± 5.3 & 59.5 ± 3.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, respectively) were consistent with those reported for similarly trained athletes (Daniels & Daniels, 1992; Maughan & Leiper, 1983; Padilla *et al.*, 1992;).

This study identified a positive relationship between $\dot{V}O_{2\,max}$ and body size (BM & FFM) confirming that this influence needs to be accounted for before meaningful gender comparisons can be made. To account successfully for this influence the scaling model must express values for $\dot{V}O_{2\,max}$ that are independent of body size (BM or FFM). Any relationship found between these $\dot{V}O_{2\,max}$ values and body size highlights the failure of the model to remove this influence and indicates that the data have been distorted which will bias interpretation.

The body mass and fat free mass ratio standard models were successful in rendering $\dot{V}O_{2\,max}$ values independent of body mass or fat free mass (see Figures 4·3 & 4·6) and justifies their use as an appropriate scaling methodology in this sample. This surprising finding would indicate that the true sample-specific scaling exponent for both body mass and fat free mass is close to unity.

Both Power Function Ratio models (0.67 & 0.75) failed to render $\dot{V}O_{2\,max}$ independent of body mass and their use would have lead to distortion of the data. In identifying this lack of independence the positive relationships in the men and women for both models suggest that the true sample-specific body mass exponent is higher than 0.67 and 0.75 and hence the data had been under scaled. As identified by the suitability of the body mass and fat free mass ratio standards, the true sample specific body mass exponent will be close to unity. The subsequent under scaling has given an arithmetic advantage to the heavier participants and, due to the men being heavier than the women, will have led to an over estimation of the gender difference in $\dot{V}O_{2\,max}$ (32 % v 25 % from the body mass allometric model). Although, these power function models are not appropriate in this sample, it is interesting to note that mean values expressed for the men are similar to values reported for similarly trained (elite) athletes. Using a 2/3 body mass exponent, Åstrand and Rodahl (1986) reported values of close to 300 ($ml \cdot BM^{-0.67} \cdot min^{-1}$) in a group of Norwegian top endurance athletes, which compares well to the value of 296 found in this study. In Svedenhag and Sjödin (1994) investigation into running economy in middle and long distance runner, they reported $\dot{V}O_{2\,max}$ values of 202 and 214 ($ml \cdot BM^{-0.75} \cdot min^{-1}$), respectively, using a 0.75 body mass exponent, which again is similar to the mean value of 211 reported in this study.

It was confirmed in both the body mass and fat free mass allometric models that the men and women shared the same relationship between $\dot{V}O_{2\,max}$ and body mass and fat free mass. This confirmed that scaled values for $\dot{V}O_{2\,max}$ could be constructed using a common body mass or fat free mass exponent and that gender comparison was appropriate. The identified common exponents of 0.94 for body mass and 0.98 for fat free mass were close to unity indicating why the body mass and fat free mass ratio standards scaled the data so well in this sample. Using the allometric models and logarithmic transformation, the error was found to be normally distributed and additive and so suitable for a parametric test (Nevill & Holder, 1994).

As a post hoc analysis to confirm whether the same was true in the body mass and fat free mass ratio standards, absolute residuals were calculated (|mean ratio value - individual ratio value|) and, as appropriate, correlated with body mass and fat free mass. The absolute residuals from the body mass ratio standard were positively related ($R = 0.357$, $p = 0.038$) with body mass, indicating that the error is multiplicative and unsuitable for parametric analysis without transformation. In contrast, there was no relationship between the absolute residuals from the fat free mass ratio standard and fat free mass ($R = -0.206$, $p = 0.242$) indicating that the error was additive and suitable for analysis. So although the body mass ratio standard and allometric model were successful in removing the influence of body mass, the body mass allometric model was superior in that it accounted for the heteroscedasticity in $\dot{V}O_{2\,max}$ and body mass leading to an unbiased interpretation. Using fat free mass as the body size variable the ratio standard was successful in scaling $\dot{V}O_{2\,max}$ so negating the need, in this sample, for the allometric model and subsequent logarithmic transformation.

Using the body mass allometric model the gender difference in $\dot{V}O_{2\,max}$ was estimated as 25 %, which is slightly higher than values reported by Daniels and Daniels (1992) and Padilla *et al.* (1992). This is to be expected as the sample in both studies were of National standard and should be considered more 'elite' than the participants used in this study. Changing the body size variable to fat free mass, so accounting for the confounding influence of body fat, the gender difference in $\dot{V}O_{2\,max}$ was reduced to 9 %. This difference is the same as reported by Johnson, Longford, Nevill and Winter (1998) in their investigation into $\dot{V}O_{2\,max}$ in elite middle and long distance runners.

In choosing the most appropriate allometric model one must consider the question that is being asked. The body mass allometric model improves description of between- and within-subject differences in performance. For example, running performance would tend to improve through reduction in body fat, a change that would be detected using body mass as your size variable and not fat free mass. However, this study is not seeking a surrogate for performance, it is comparing the aerobic qualitative characteristics of tissue in men and women. Fat free mass as the body size variable has greater validity than body mass because it is not confounded by between-subject and gender differences in body composition. As Batterham *et al.* (1999, *p.* 1317) stated '...as much as ≈ 95 % of the oxygen....at $\dot{V}O_{2\,peak}$ is bound for a 'single sink' in the skeletal muscle mitochondria, it follows that estimated fat free mass may be a judicious choice as an indicator of body size'.

The finding of a fat free mass scaling exponent of near unity, which justified the use of a simple ratio standard ($ml \cdot FFM^{-1} \cdot min^{-1}$), has been reported before. Vanderburgh and Katch (1996) investigated $\dot{V}O_2$ max in 94 women and reported a fat free mass exponent of 1.04 (SEE ± 0.13). Similar findings have also been reported by Davies, Dalsky and Vanderburgh (1995) and Batterham *et al.* (1999).

In summary, this study has investigated the effectiveness of the ratio standard and allometry to express $\dot{V}O_{2\,max}$ free from the influence of size and so meaningfully explore the gender difference. The fat free mass ratio standard was found to be the simplest and most appropriate model and estimated this gender difference at 9 %. With only 34 participants the power of this study was high at 98

% (83.6 ± 3.9 & 77.0 ± 5.5 $ml \cdot FFM^{-1} \cdot min^{-1}$, values are mean $\pm$ SD for the men and women respectively, $\alpha = 0.05$) but with a small range of body masses (35.0 - 50.3 kg & 51.3 - 71.5 kg, in the women and men, respectively) the findings from this study should be treated with caution and await further investigation.

Chapter 5

STUDY 2

Modelling maximal oxygen uptake of International standard male and female endurance athletes.

INTRODUCTION

Important to the success in aerobic sporting disciplines is an athlete's ability to extract, transport and utilise oxygen maximally ($\dot{V}O_{2\,max}$). Elite aerobic athletes, due to their many years of training and blessed with the appropriate 'aerobic' genetic endowment, tend to have the highest values recorded. Any such 'elite' population should offer the chance to explore the upper limits of the human body to extract, transport and utilize oxygen and allow standards to be constructed by which others can be compared.

Since the early work of by A.V. Hill in the 1920's, the upper limit of maximal aerobic power has been of interest to many researchers. Robinson, Edwards and Dill published an article titled 'New records in human power' in 1937, reporting a measured $\dot{V}O_{2\,max}$ of 81.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (5.35 $l{\cdot}min^{-1}$) on Don Lash, the then 2-mile world record holder. Later in 1955, Åstrand published an article with the same title reporting a higher value of 81.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (5.88 $l{\cdot}min^{-1}$) for a male cross-country skier (S. Jernberg). A value of 68.4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (3.97 $l{\cdot}min^{-1}$) was also reported for a female cross-country skier (A. L. Eriksson). In their paper of 1967, Saltin and Åstrand reported an even higher value of 85.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (5.66 $l{\cdot}min^{-1}$) for a male World and Olympic champion cross country skier and 66.3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (3.78 $l{\cdot}min^{-1}$) for a female Swedish champion skier. More recently in Saltin, Larsen, Terrados, Bangsbo, Bal, Kim, Svedenhag and Rolf's (1995) comparison of Kenyan and Scandinavian runners, the highest individual value was that of a Kenyan runner of 85.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$. The highest value reported for a woman is that of 78.6 $ml{\cdot}kg^{-}$

$^{1}\cdot min^{-1}$ for an Olympic Gold Medalist in the marathon (Daniels, Scardina, Hayes & Folley, 1986).

Much work can also be found for other aerobic sports which advantage larger individuals but the values quoted ($ml\cdot kg^{-1}\cdot min^{-1}$) are never as impressive. Rowing is a weight-supported sport and in non-lightweight competition it is advantageous for rowers to be large (Shephard, 1998). Values reported tend to be the largest absolute values for VO_{2max}, for example Secher (1990) reported values of up to 6.6 $l\cdot min^{-1}$ in World Champion oarsmen. However, when attempts are made to account for their size the value that is used traditionally to compare aerobic power, the ratio standard, equates to a value of just over 70 $ml\cdot kg^{-1}\cdot min^{-1}$.

Obviously this influence of size needs to be removed before meaningful inferences can be made. The use of the traditional ratio standard has been shown to be inappropriate (Batterham *et al.*, 1997; Katch, 1972, 1973; Katch & Katch, 1974; Nevill *et al.*, 1992; Packard & Boardman, 1987; Tanner, 1949; Vanderburgh *et al.*, 1996 & Winter, 1992) and tends to '...penalize heavy individuals' (Åstrand & Rodahl, 1986, *p.* 399,) so leading to possible misinterpretation. However, there use is virtually universal.

In addition to using the ratio standard, a few 'enlightened' investigators have also expressed values for $\dot{V}O_{2\,max}$ using a power function ratio with either 0.67 or 0.75 as the body mass (BM) exponent ($ml\cdot kg^{-b}\cdot min^{-1}$). Svedenhag and Sjödin (1994) in their investigation of running economy and step length, reported mean values of 202 ($ml\cdot kg^{-0.75}\cdot min^{-1}$) for middle-distance runners (n = 14) and 214 for long distance runners (n = 12). Åstrand and Rodahl's (1986) rework of Vaage and Hermansen's data from the Norwegian National team using a body mass exponent of 0.67, reported a mean value of ~ 300 ($ml \cdot kg^{-0.67} \cdot min^{-1}$). Secher (1983) published values of International standard oarsmen of 288 (n = 14) ($ml \cdot kg^{-0.67} \cdot min^{-1}$) and 291 ($n$ = 13), which incidentally compare well with the values reported above by Åstrand & Rodahl (1986). Although the use of such allometric modelling could well be an improvement on the ratio standard, the indiscriminant use of power function ratios without checking the suitability of the body mass exponent can also lead to misinterpretation, as demonstrated in Study **1**. No study has yet to investigate maximal aerobic power in National/International aerobic athletes using non-linear allometric modeling.

In non-elite samples, a wide range of body mass exponents have been reported and this lack of agreement has recently provoked some lively debate (Batterham *et al.*, 1999; Nevill, 1994). As discussed by Batterham *et al.* (1999), this variety of sample-specific body mass exponents can be attributed to factors such as: small sample size (Rogers, Olson & Wilmore, 1995); small body size range (Calder, 1987); a failure to account for covariates (Heil, 1997; Nevill & Holder, 1995); and the use of the most appropriate body size variable (BM or FFM) (Batterham *et al.*, 1999; Vanderburgh & Katch, 1996).

Taking into consideration these shortcomings, the purpose of this study was to identify the most appropriate way to express $\dot{V}O_{2\,max}$ in International standard male and female endurance athletes. By doing so, this study also aims to construct standards for $\dot{V}O_{2\,max}$ by which other endurance athletes can be meaningfully compared.

METHODS

Participants

A total of 119 (50 male, 69 female) middle- and long-distance runners (MDR & LDR, respectively) and light and heavyweight rowers (LWR & HWR, respectively) who had represented the United Kingdom at an International level provided written informed consent. Data for all participants were collected at the British Olympic Medical Centre (Harrow, UK) during 1994-1997. Details of the participants are provided in Table 5·1.

Protocol

Body mass was assessed to the nearest 0.05 kg using beam balance scales (Avery Berkel, Dublin, Ireland). Following the guidelines set by Weiner and Lourie (1981), body density was estimated from the log of the sum of four skin-fold measurements (Durnin & Wormersley, 1974) and percentage body fat estimated using Siri's equation (1961).

Using BASES criteria (Hale *et al.*, 1988), VO_{2max} was determined on the MDR's and LDR's during an incremental continuous test to volitional exhaustion on motorised treadmills (Powerjog M30, Birmingham, Sport Engineering), and during a discontinuous test to volitional exhaustion on a rowing ergometer (Concept IIC, Nottingham, UK) for the LWR's and HWR's. Expired air was collected and analysed via on-line systems (Jaeger EOS-Sprint, Market Harborough, UK; Mijnhardt Oxycon Champion, Bunnik, Holland) which were calibrated immediately before and verified immediately after testing with gases of known concentration and a syringe of known volume.

Analyses

All analyses were made using SPSS version 9 (SPSS Inc., Chicago, IL). Descriptive statistics were performed on the summary data. Using graph plots and bivariate correlation, preliminary analyses were made of the relationship between body mass and fat free mass with $\dot{V}O_{2\,max}$. The following models were used to evaluate $\dot{V}O_{2\,max}$:

1. Absolutely, with $\dot{V}O_{2\,max}$ expressed in $l \cdot min^{-1}$ and compared using 2×4 (Gender by endurance group) factorial analysis of variance (ANOVA).
2. Ratio standard, constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass (BM) and expressed in $ml \cdot BM^{-1} \cdot min^{-1}$. Values again compared using 2×4 factorial ANOVA.
3. Fat free mass ratio standard, constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by fat free mass (FFM) and expressed in $ml \cdot FFM^{-1} \cdot min^{-1}$. Values compared using 2×4 factorial ANOVA.
4. Power function ratio, constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass raised to the power 0.67 ($BM^{0.67}$) and expressed in $ml \cdot BM^{-0.67} \cdot min^{-1}$. Values compared using 2×4 factorial ANOVA.
5. Body mass allometric model. Influence of body mass on $\dot{V}O_{2\,max}$ was investigated using the allometric model proposed in Study **1**, endurance sport was

also incorporated into the model as a categorical variable (4 levels), so producing an expression of the form:

$$\dot{V}O_{2\,max} = BM^{b} \cdot \exp(a + c \cdot sex + d \cdot sport) \cdot \in$$

where $\in$ represents a random multiplicative error term. The model was linearised by taking the natural logarithm (*ln*) of $\dot{V}O_{2\,max}$ and body mass. Hence:

$$ln\,\dot{V}O_{2\,max} = b \cdot ln BM + a + c \cdot sex + d \cdot sport + ln\in$$

To confirm whether men and women and endurance sport could be compared using the same body mass scaling exponent, the homogeneity of the body mass coefficient (slope) was first verified by including *sex* × *ln*BM, *sport* × *ln*BM and *sex* × *sport* × *ln*BM variables into the linearised model to check for interaction. Following verification, coefficients *a*, *b*, *c* and *d* were identified using ANCOVA. Power function ratios were then constructed by dividing $\dot{V}O_{2\,max}$ ($ml \cdot min^{-1}$) by body mass raised to the identified pooled exponent (BM^{b}) and expressed in $ml \cdot BM^{-b} \cdot min^{-1}$. Following recommendations from Study **1**, individual body mass exponents for each endurance sport by gender were also estimated.

6. Fat free mass allometric model. Similar to **4** but body mass was replaced with fat free mass to create a linearised model of the form:

$$ln\,\dot{V}O_{2\,max} = b \cdot ln FFM + a + c \cdot sex + ln\in$$

Homogeneity of the fat free mass coefficient (slope) was first verified by including *sex* × *ln*FFM, *sport* × *ln*FFM and *sex* × *sport* × *ln*FFM variables into the linearised model to check for interaction. Following verification, coefficients *a*, *b*, *c* and *d* were identified using ANCOVA. Power function ratios were then constructed ($ml \cdot FFM^{-b} \cdot min^{-1}$) and individual fat free mass exponents for each endurance sport by gender estimated.

Further to the suitability of either allometric model, an exploratory analysis of the influence of age was also investigated using the model proposed by Nevill and Holder (1995):

$$\dot{V}O_{2\,max} = BM^{b} \cdot \exp(a + c \cdot age + d \cdot age^{2}) \cdot \in$$

Where appropriate, variables *sex* and *sport* were also included in the model, to produce an expression of the form:

$$\dot{V}O_{2\,max} = BM^{b} \cdot \exp(a + c \cdot age + d \cdot age^{2} + f \cdot sex + g \cdot sport) \cdot \in$$

A linear function was constructed by taking the natural logarithm (*ln*) of $\dot{V}O_{2\,max}$ and body mass or fat free mass, represented in the form:

$$ln\,\dot{V}O_{2\,max} = b \cdot ln BM + a + c \cdot age + d \cdot age^{2} + f \cdot sex + g \cdot sport + ln \in$$

Parameter estimates were identified by means of multiple regression. Further to confirming the significance of the *age* and *age*^{2} parameters, the validity of age as a covariate was checked by identifying the age for maximum $\dot{V}O_{2\,max}$. This was achieved by differentiating the model with respect to age:

$$\frac{d\dot{V}O_2\ max}{dage} = c + 2 \cdot d \cdot age\,\delta$$

At optimum $\dot{V}O_{2\,max}$ the gradient should be zero:

$$\therefore \qquad 0 = c + 2 \cdot d \cdot \mathrm{age}$$

$$\therefore \qquad \mathrm{age} = \frac{-c}{2 \cdot d}$$

Model diagnostics

To check the suitability of each model to render $\dot{V}O_{2\,max}$ free from the influence of size, the values constructed were plotted against the measure of body size (BM or FFM). For both allometric models (BM & FFM) the Kolmogorov-Smirnov test was used to check that the residuals about regression were normally distributed and multiplicative heteroscedasticity was confirmed by correlating the absolute residuals from the logged model (BM or FFM) with *ln*BM of *ln*FFM respectively.

As appropriate, differences between groups (sport) were investigated using post-hoc Tukey *b*. Level of significance was set at $p < 0.05$.

Table 5·1: Physical characteristics of subjects, values are mean and SD.

	LDR		MDR		LWR		HWR	
	Male	Female	Male	Female	Male	Female	Male	Female
	n = 10	*n* = 10	*n* = 11	*n* = 19	*n* = 13	*n* = 12	*n* = 16	*n* = 28
Age (years)	26.6	24.9	21.2	24.3	28.5	26.8	24.4	26.0
	5.4	6.7	2.1	5.3	4.4	4.4	3.2	5.0
Body mass (kg)	62.2	49.6	67.1	55.6	73.9	60.3	93.3	75.9
	5.4	5.2	4.7	5.0	1.3	3.1	6.0	7.2
Stature (m)	1.74	1.62	1.80	1.66	1.82	1.68	1.93	1.79
	0.03	0.06	0.06	0.05	0.03	0.05	0.04	0.05
Body fat (%)*	8.5	16.8	9.4	17.7	10.8	19.9	11.4	23.5
	2.2	2.2	0.4	0.4	0.9	2.8	2.4	3.8
Fat free mass* (kg)	56.9	41.3	61.0	45.5	65.9	48.3	82.6	57.9
	4.7	4.5	4.3	3.9	2.5	1.8	5.3	4.6
VO_{2max} ($l \cdot min^{-1}$)	4.82	3.18	5.09	3.50	5.36	3.62	6.48	4.23
	0.50	0.40	0.52	0.35	0.29	0.18	0.82	0.40

*Missing value for Male (*n* = 10) and Female (*n* = 18) MDR's.

Source: Appendix 5·1

RESULTS

Summary data both for men and women by endurance group are presented in Table 5·1, individual data collated in Appendix 5·1. There was no gender difference in age ($F = 0.152, p = 0.697$) although there were age differences (mean ± SEM) between endurance groups ($F = 4.70, p = 0.004$). The LWR were identified as the oldest group (27.6 ± 1.0 years) and MDR the youngest (22.8 ± 0.9 years), so warranting further investigation of the effect of age on $\dot{V}O_{2\,max}$. Not surprisingly, the men, on average, had greater mass than the women ($F = 171.6, p < 0.001$) and there were body mass differences between endurance groups ($F = 170.0, p < 0.001$), with the HWR (84.6 ± 1.1 kg) having the greatest and LDR (55.9 ± 1.2 kg) the least. Similar gender and sport differences were also identified in fat free mass ($F = 502.5$ & $154.1, p < 0.001$, respectively). Unsurprisingly, the women had a higher percentage of body fat than the men ($F = 296.3, p < 0.001$) and there were body fat percentage differences between sports ($F = 17.4, p < 0.001$). Moreover, Figure 5·2 illustrates the positive relationship between body fat percentage and body mass in men ($R = 0.431, p = 0.002$) and women ($R = 0.762, p < 0.001$) which would indicate that the larger the athlete the higher their body fat percentage.

Grouping the data by gender, a positive relationship between $\dot{V}O_{2\,max}$ with body mass is clearly evident in Figure 5·1a, with correlation coefficients of 0.882 and 0.858 for the men and women respectively ($p < 0.001$). A similar relationship was also found between $\dot{V}O_{2\,max}$ and fat free mass ($R = 0.879$ & $0.878, p < 0.001$, respectively).

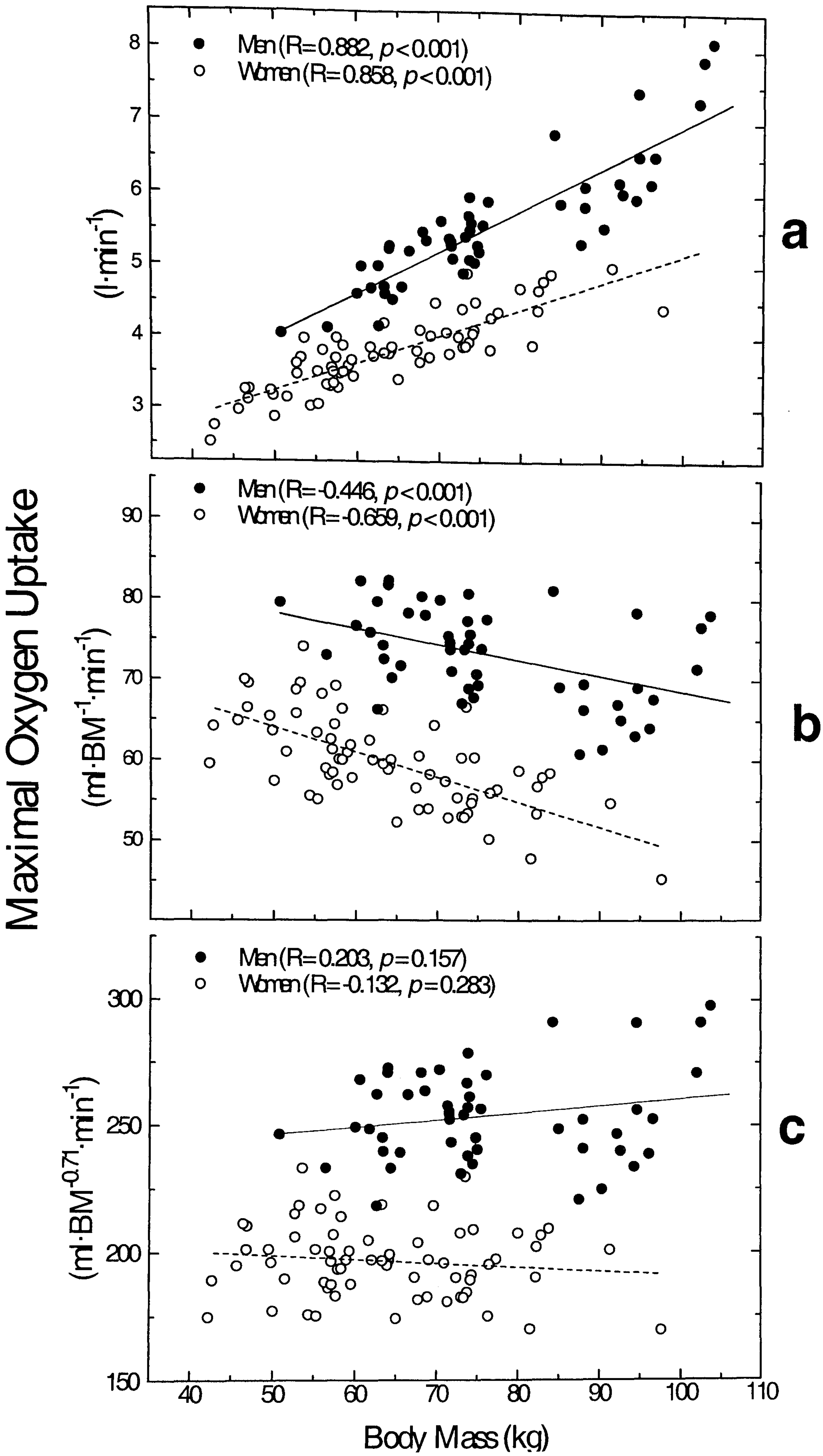

Figure 5·1: Maximal oxygen uptake related to body mass in International standard male and female endurance athletes.

1. Absolute values for $\dot{V}O_{2\,max}$ are summarised in Table 5·2 and listed in Appendix 5·1. Not surprisingly there was a gender influence in $\dot{V}O_{2\,max}$ ($F = 389.2, p < 0.001$) with the values ($l \cdot min^{-1}$) for the men (5.44 ± 0.07) being, on average, 50 % higher than the women (3.63 ± 0.06). Independent of gender (men & women's data pooled), there was also a clear sport effect ($F = 49.5, p < 0.001$) with the HWR, the group with greatest body mass, having the largest values (5.36 ± 0.07) and the LDR, the group with the least body mass, having the lowest (4.00 ± 0.11). No particular inference can be made from these findings, as $\dot{V}O_{2\,max}$ needs to be adjusted for differences in body size.

2. Body mass ratio standards were calculated and summary presented in Table 5·2. As an entire group the mean $\dot{V}O_{2\,max}$ ($ml \cdot BM^{-1} \cdot min^{-1}$) for the men ($73.8 \pm 0.1$) was 21 % higher ($F = 201.3, p < 0.001$) than that of the women (60.8 ± 0.1). Independent of gender (men & women's data pooled), there was still a sport effect ($F = 18.3, p < 0.001$) but in juxtaposition to **1**, the group with the least body mass, the LDR, now has the highest value (70.7 ± 1.1) whereas the group with the greatest body mass, the HWR, has the lowest (62.6 ± 0.7). As illustrated in Figure 5·1b, when these values were correlated with body mass, coefficients of -0.446 and -0.659 ($p < 0.001$), for the men and women respectively, indicate that the body mass ratio standard has not rendered $\dot{V}O_{2\,max}$ independent of body mass and is therefore inappropriate.

3. Fat free mass ratio standards were calculated and summary presented in Table 5·2. Maximal oxygen uptake values ($ml \cdot FFM^{-1} \cdot min^{-1}$) for the men ($82.2 \pm 0.8$) were, on average, 9 % higher ($F = 39.1, p < 0.001$) than the women (75.5 ± 0.7).

Independent of gender (men & women's data pooled), there was still a sport effect ($F = 6.30, p = 0.001$) and, similar to **2**, the group with the least body mass, the LDR, had the highest value (80.8 ± 1.2) with the two groups with the greatest body mass, the HWR and LWR, the lowest (75.7 ± 0.8 & 78.2 ± 1.1, respectively). Again similar to **2**, when these values were correlated with fat free mass a negative relationship was found between the men ($R = -0.349, p = 0.014$) and women ($R = -0.363, p = 0.003$) indicating that the values were not independent of fat free mass and inappropriate in this sample.

4. Power function ratios using a body mass exponent of 0.67 are presented in Table 5·2. Maximal oxygen uptake values ($ml \cdot BM^{-0.67} \cdot min^{-1}$) for the men ($304 \pm 3$) were, on average, 30 % higher ($F = 336.4, p < 0.001$) than the women (234 ± 3). In contrast to model **2** and **3**, there was now no difference between sport ($F = 0.511, p = 0.675$). These values were correlated with body mass and no relationship was found in the women ($R = -0.025, p = 0.838$) although a relationship was found in the men ($R = 0.296, p = 0.037$). This indicates the suitability of the power function ratios for the women but that a body exponent of 0.67 was inappropriate for the men and under scaled the data.

Table 5·2: Expression of maximal oxygen uptake, values are mean and SEM.

	LDR		MDR		LWR		HWR	
	Male	Female	Male	Female	Male	Female	Male	Female
	n = 10	n = 10	n = 11	n = 19	n = 13	n = 12	n = 16	n = 28
Absolute	4.82	3.18	5.09	3.50	5.36	3.62	6.48	4.23
($l \cdot min^{-1}$)	0.17	0.14	0.16	0.09	0.08	0.05	0.21	0.08
BM Ratio Standard	77.4	64.1	75.8	63.2	72.5	60.0	69.3	55.9
($ml \cdot BM^{-1} \cdot min^{-1}$)	1.2	1.5	1.6	1.3	1.0	0.9	1.6	0.8
FFM Ratio Standard*	84.6	77.0	84.3	77.2	81.4	75.0	78.3	73.2
($ml \cdot FFM^{-1} \cdot min^{-1}$)	1.4	1.6	1.6	1.6	1.3	0.8	1.8	1.0
BM Power Function (0.67)	302	232	304	238	300	232	310	233
($ml \cdot BM^{-0.67} \cdot min^{-1}$)	6	6	7	5	4	3	8	3
BM Allometric Model	254	197	255	201	250	195	256	194
($ml \cdot BM^{-0.71} \cdot min^{-1}$)	5	5	6	4	3	2	6	3
FFM Allometric Model*	167	144	169	147	165	144	165	145
($ml \cdot FFM^{-0.83} \cdot min^{-1}$)	3	3	3	3	2	2	4	2

*Missing value for Male (n = 10) and Female (n = 18) MDR's.
Source: Appendix 5·1

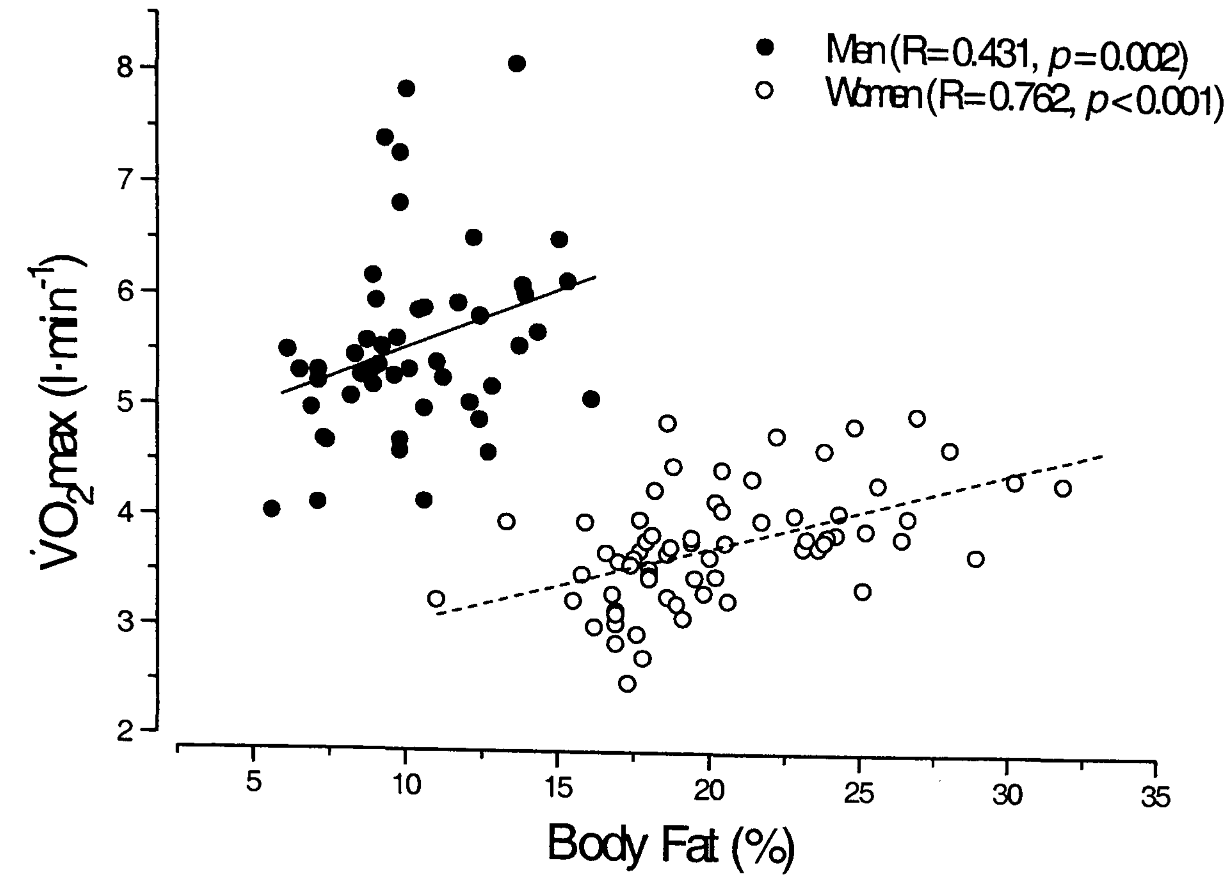

Figure 5·2: Relationship between absolute maximal oxygen uptake and body fat (%) in the men and women.

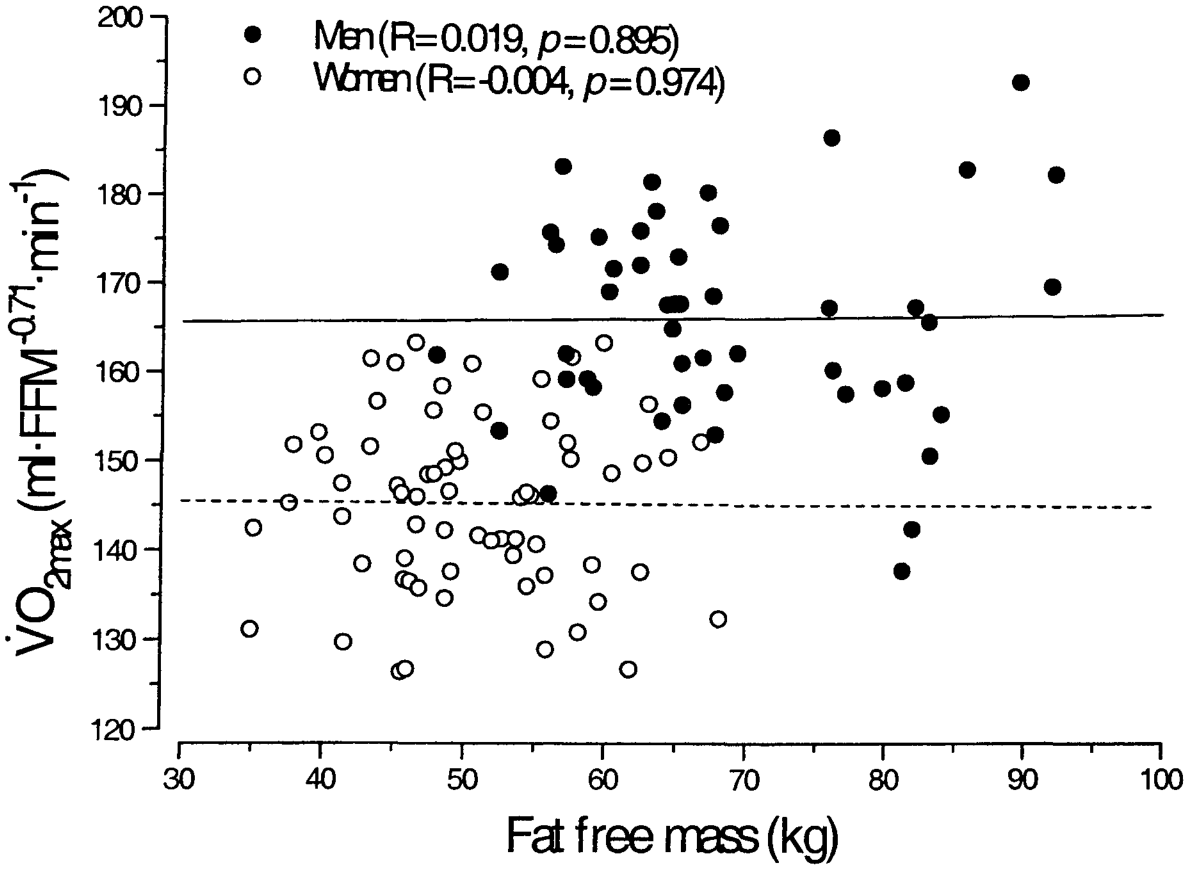

Figure 5·3: Relationship between $\dot{V}O_{2\,max}$, expressed using the fat free mass allometric model, and fat free mass in the men and women.

5. Individual body mass exponents for each sport by gender were estimated and are presented in Table 5·3. There was no evidence of a *sex* × *ln*BM ($t = 1.43$, $p =$ 0.156), *sport* × *ln*BM ($t = 1.09$, $p = 0.277$) or *sex* × *sport* × *ln*BM ($t = 0.655$, $p =$ 0.514) interaction and thus these variables where removed from the model. This confirms the homogeneity of slopes between sport and gender and justifies the analysis of the data using the same body mass scaling exponent (b). Further analysis also revealed no effect of sport ($t = 1.42$, $p = 0.158$) and the variable was also removed from the model. The body mass allometric model explained 91.2 % ($R = 0.955$, SEE = 0.0720) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*BM (0.712 ± 0.037), *sex* (0.255 ± 0.015) and intercept (-1.630 ± 0.153) were all significant ($p < 0.001$). The model was linearised by taking the antilogarithm of $ln\,\dot{V}O_{2\,max}$ and *ln*BM, so producing the following allometric model:

$$\dot{V}O_{2\,max} = BM^{0.712} \cdot \exp(-1.630 + 0.255 \cdot sex) \cdot \epsilon$$

The value of the *sex* parameter equates the difference in $\dot{V}O_{2\,max}$ between the men and women as 29 % ($e^{0.255}$). Using the common body mass exponent, $\dot{V}O_{2\,max}$ values were calculated ($ml \cdot BM^{-0.71} \cdot min^{-1}$) and presented in Table 5·2. Correlating these values with body mass, coefficients of 0.203 ($p = 0.157$) and -0.132 ($p = 0.283$), for the men and women respectively, were identified indicating that $\dot{V}O_{2\,max}$ had been successfully expressed free from the influence of body mass. The influence of age was also investigated by introducing variables *age* and *age*^{2} in the model. This model explained 92.1 % ($R = 0.960$, SEE = 0.0687) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*BM (0.684 ± 0.036), *sex* (0.258 ± 0.014), *age* (0.0345 ± 0.0118), age^2 (-0.000607 ± 0.000229) and intercept (-1.983 ± 0.187) were all significant ($p <$ 0.01). Introducing the parameters *age* and age^2 into the differential equation outlined in the methods, produced the following estimate for the optimum age for $\dot{V}O_{2\,max}$:

$$\text{age} = \frac{-c}{2 \cdot d} = -0.03499/2 \cdot 0.000607 = 28.4 \text{ years}$$

6. Individual fat free mass exponents for each sport by gender were estimated and are presented in Table 5·3. There was no evidence of a *sex* × *ln*FFM (t = 0.073, p = 0.942), *sport* × *ln*FFM (t = 0.805, p = 0.423) or *sex* × *sport* × *ln*FFM (t = 0.572, p = 0.568) interaction and thus these were removed from the model. Further analysis also revealed no effect of *sport* (t = 1.16, p = 0.158) and this variable was also removed from the model. The fat free mass allometric model explained 92.0 % (R = 0.959, SEE = 0.0690) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*FFM (0.831 ± 0.041), *sex* (0.135 ± 0.018) and intercept (-1.930 ± 0.161) were all significant ($p < 0.001$). The model was linearised by taking the antilogarithm of $ln\,\dot{V}O_{2\,max}$ and *ln*FFM producing the following allometric model:

$$\dot{V}O_{2\,max} = \text{FFM}^{0.831} \cdot \exp(-1.930 + 0.135 \cdot \text{sex}) \cdot \in$$

The value of the sex parameter was lower than in **5** and equates to a 14 % difference in $\dot{V}O_{2\,max}$ between the men and women ($e^{0.135}$). Using the common fat free mass exponent, $\dot{V}O_{2\,max}$ values were calculated (ml·FFM$^{-0.83}$·min^{-1}) and are presented in Table 5·2. Correlation of these values with fat free mass (see

Figure 5·3) produced coefficients of 0.019 ($p = 0.895$) and -0.004 ($p = 0.974$), for the men and women respectively, and indicated that $\dot{V}O_{2\,max}$ had been successfully expressed free from the influence of fat free mass. As for the body mass allometric model, the influence of age was also investigated by introducing variables *age* and *age*^{2} in the model. This model explained 92.7 % (R = 0.963, SEE = 0.0664) of the variance in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) for *ln*FFM (0.802 ± 0.041), *sex* (0.142 ± 0.017), *age* (0.0304 ± 0.0121), *age*^{2} (-0.000525 ± 0.000233) and intercept (-2.237 ± 0.194) were all significant ($p < 0.05$). Using the above differential equation, the following estimate optimum age for $\dot{V}O_{2\,max}$ was derived:

$$\text{age} = \frac{-c}{2 \cdot d} = -0.0304/2(-0.000525) = 28.9 \text{ years}$$

Table 5·3: Body mass and fat free mass exponents identified for each sport by gender (± SEE).

	Body mass model		Fat free mass model	
	Men	Women	Men	Women
LDR	1.048 (0.185)	1.062 (0.243)	1.088 (0.223)	1.037 (0.221)
MDR	1.172 (0.312)	0.665 (0.216)	1.189 (0.282)	0.768 (0.239)
LWR	1.375 (0.812)	0.455 (0.270)	0.455 (0.400)	0.825 (0.328)
HWR	1.354 (0.359)	0.628 (0.158)	1.321 (0.381)	0.777 (0.175)

Model diagnostics

The residuals from both allometric models (BM & FFM) were normally distributed ($p > 0.200$) and no relationship was found between the absolute residuals from the body mass allometric model and *ln*BM ($R = 0.109$, $p = 0.241$) or the fat free mass allometric model and *ln*FFM ($R = 0.137$, $p = 0.142$) confirming that the error had been correctly treated by the logarithmic transformation.

DISCUSSION

In this sample of elite endurance athletes there is a relationship between body mass and fat free mass with $\dot{V}O_{2\,max}$ over a wide range of body sizes (≈ 2.5 fold). This wide range is important if meaningful scaling expressions are to be derived (Batterham *et al.*, 1999). Moreover, as each athlete was selected to represent their country through success in their particular sport, the sample could be considered to be homogenous in terms of training status and genetic aerobic endowment. Also, as this type of testing is performed regularly on these athletes at the BOMC, this sample was habituated to the procedures and equipment used.

Mean absolute $\dot{V}O_{2\,max}$ for the male HWR was 6.5 $l{\cdot}min^{-1}$, which is one of the highest values reported for any group of athletes. One participant had a $\dot{V}O_{2\,max}$ of 8.1 ($l{\cdot}min^{-1}$), which is the highest absolute value ever reported and it is not surprising that this athlete has won numerous World Titles and more than one Olympic Gold Medal.

Absolute $\dot{V}O_{2\,max}$ was related both to body mass and fat free mass demonstrating the need to remove the influence of body size to allow meaningful comparison between gender and sport. Even in this homogenous group, $\dot{V}O_{2\,max}$ was also found to be influenced by age so warranting further investigation.

The body mass ratio standard identified a gender and sport difference in $\dot{V}O_{2\,max}$ although the negative relationship observed between the $\dot{V}O_{2\,max}$ values ($ml{\cdot}BM^{-1}{\cdot}min^{-1}$) and body mass show that the data had been 'over-scaled'. This 'over-scaling' disadvantaged the athletes with the greatest mass (rowers/men) and advantaged the athletes with the least (runners/women) and distorted the data. The gender difference in $\dot{V}O_{2\,max}$ was under estimated and the difference found between sports artificial. The fat free mass ratio standard was an improvement on the body mass ratio standard as it removed the confounding influence of the gender specific body fat and, as illustrated in Figure 5·2, the between sport difference in body fat percentage. However, similar to the body mass ratio standard, the fat free mass ratio standard failed to remove the influence of body size and again over-scaled the data.

Power function ratios using 0.67 as the body mass exponent revealed a gender difference in $\dot{V}O_{2\,max}$ but no difference between sports. No relationship was observed between $\dot{V}O_{2\,max}$ (ml·BM$^{-0.67}$·min^{-1}) and body mass in the women demonstrating that the values had been expressed independent of body size and scaled correctly. However, a positive relationship was found in the men suggesting that the data had been under scaled and the use of a body mass exponent of 0.67 was inappropriate.

Both allometric models found that men and women from all sports shared the same relationship between $\dot{V}O_{2\,max}$ and body size (BM or FFM) confirming that gender and sport comparison could be made using a common body mass or fat free mass exponent. The body mass allometric model accounted for 91 % of the variability in $\dot{V}O_{2\,max}$ and estimated a gender difference of 29 % but identified no difference between sports. No relationship was found between the constructed $\dot{V}O_{2\,max}$ values (ml·BM$^{-0.71}$·min^{-1}) and body mass confirming that the data had been correctly scaled. The 95 % confidence of the body mass exponent of 0.71 (0.64, 0.78) encompasses 0.67, which would justify the use of power function ratios (ml·BM$^{-0.67}$·min^{-1}) to scale the data. However as discussed above, the use of such ratios was found to be inappropriate in the men. The fat free mass allometric model accounted for 92 % of the variability in $\dot{V}O_{2\,max}$ and again was found to appropriately scale the data. The use of fat free mass removes the confounding influence of body fat and, subsequently, the model identified a lower estimate of the gender difference in $\dot{V}O_{2\,max}$ (14 %) and again no difference between sports. The fat free mass exponent of 0.83 was higher than the body mass exponent and its 95 % confidence interval (0.75, 0.91) does not encompass 0.67.

The influence of age was also investigated as a possible covariate using the quadratic model (*age* & *age*^{2}) proposed by Nevill & Holder (1995). Both allometric models found that the age parameters successfully accounted for variability in $\dot{V}O_{2\,max}$ and values of 28.4 and 28.9 years for optimum age for $\dot{V}O_{2\,max}$ were estimated, for the body mass and fat free mass models respectively. These compare well with the literature, which would expect to see increases in an aerobic athletes' $\dot{V}O_{2\,max}$ to plateau in their 20's (Hermansen, 1974) and '...after age 25, $\dot{V}O_{2\,max}$ declines steadily at about 1 % per year' (McArdle *et al.*, 1991, *p*. 221). Moreover even in this group of elite aerobic athletes there was more than a two-fold age range (15 - 39 years), which lends greater validity to the parameters estimated. The introduction of age in the body mass allometric model lowered the estimated body mass exponent to 0.684 (± SEE), which is even closer to the 'surface-law' theoretical value of 0.67 used in the power function ratio above. Adjusting for this influence of age, the power function ratio [$ml \cdot BM^{-0.67} \cdot min^{-1} \cdot exp(0.0345 \cdot age - 0.000607 \cdot age^2)^{-1}$] was now found to be independent of body mass both in the men (R = 0.224, p = 0.118) and women (R = -0.083, p = 0.499) and provides an appropriate scaling model.

Similar to the discussion in Study 1, whether to use the body mass or fat free mass allometric model depends on the research question being asked. For investigations into gender differences in $\dot{V}O_{2\,max}$ it is more appropriate to compare the oxygen using tissue in the men with the oxygen using tissue in the women, without the confounding influence of body fat. Therefore, the gender difference in $\dot{V}O_{2\,max}$ was 14 %, as identified using the fat free mass allometric model. However, care is warranted in future comparison, as there are always two ways to calculate a percentage difference dependent on which group mean is used as the denominator. The use of the smaller mean will always result in a higher apparent percentage difference than when using the larger mean. This study coded the gender variable as '0' for women and '1' for the men meaning the gender difference is calculated using the women's mean as the denominator, which is the smaller mean. For comparison, if the difference in $\dot{V}O_{2\,max}$ was estimated using the men's mean then the gender difference would be 12.6 % ($e^{-0.135}$).

This study also aimed to construct standards for $\dot{V}O_{2\,max}$ by which others could be meaningfully compared. Such comparison should be related to performance and whilst an athlete is performing their chosen sport they still have to carry their body fat as excess load. Whilst body weight is more of a factor in some sports than others, in this context it is still more valid to use body mass as the body size variable in the allometric model as it better reflects performance. Standards by which other endurance athletes can be compared could be constructed using power function ratios with 0.67 as the body mass scaling exponent ($ml \cdot BM^{-0.67} \cdot min^{-1}$) but only after the influence of age has been removed. The addition of age into the model would also broaden the use of this $\dot{V}O_{2\,max}$ standard.

This study's finding is slightly different to that illustrated by Åstrand & Rodahl (1986) in their rework of Vaage and Hermansen's data from the Norwegian National team. They found that the use of a body mass exponent of 0.67 in their power function ratio was appropriate without the need to adjust for age, although the athletes used might have been more homogenous in terms of age. However, their mean value for VO_{2max} of ~ 300 ($ml \cdot kg^{-0.67} \cdot min^{-1}$) is similar to the value of 304 ($ml \cdot kg^{-0.67} \cdot min^{-1}$) found in this study and should represent a standard by which male endurance athletes should aspire at some point in their life (~ 28 years). Even without adjusting for age the use of the power function ratio was found to be appropriate in the women and as no other study has reported values for similar elite female athletes the value of 234 ($ml \cdot kg^{-0.67} \cdot min^{-1}$) reported in this study could be adopted as a standard for comparison.

As illustrated in Table 5·3, the individual exponents from each sport by gender showed a marked variation from the pooled scaling exponents identified in either allometric model. Using body mass as the body size variable, values ranged from 0.455 in the women LWR to 1.375 in the male LWR and using fat free mass, ranged from 0.455 in the male LWR to 1.321 in the male HWR. Such variation could be attributed to the homogeneity of participants within sport and gender and, as warned by Calder (1987), illustrates the potential pitfall when trying to estimate meaningful scaling expressions from participants with a small range in body size.

This study has highlighted the shortcomings of the ratio standard (BM & FFM) and demonstrated how such indiscriminant use can distort the data and lead to a serious misinterpretation. Both allometric models successfully scaled the data and were further improved by the addition of age as a covariate. Correct adjustment for differences in body size and age revealed that the men had a higher $\dot{V}O_{2\,max}$ than the women although there was no difference found between the four categories of endurance sport. Due to the wide body-size and age range and elite nature of the sample, the findings from this study can be used to construct standards by which others can be meaningfully compared.

Chapter 6

STUDY 3

Modelling the influence of age, physical activity, body size and gender on maximal oxygen uptake in older humans.

INTRODUCTION

The decline in $\dot{V}O_{2\,max}$ from the age of about 25 has been well documented (Åstrand, 1960; Grimby & Saltin, 1966; Gerstenblith *et al.*, 1976). Explanations for this decline include: age-related changes in maximal heart rate (Rodeheffer, Gerstenblith, Becker, Fleg, Weisfeldt & Lakatta, 1984); maximal stroke volume (Julius, Amery, Whitlock, & Conway, 1967; Petrella, Nichol, Cunningham & Paterson, 1994; Thomas, Cunningham, Plyley, Boughner & Cook, 1981), maximal arterio-venous O_2 difference (Julius *et al.*, 1967) and decline in muscle oxidative capacity (Cardus, Marrades, Roca, Barbera, Diaz, Masclans, Rodriguez-Roisin & Wagner, 1998; Coggan, Spina, Rogers, King, Brown, Nemeth & Holloszy, 1995; Houmard, Weidner, Gavigan, Tyndall, Hickey & Alshami, 1998). However, the precise contribution of each factor to the decline in aerobic power has yet to be identified. The identification of causal relationships is problematic and might await longitudinal investigations but in the meantime linear multifactorial analyses of cross-sectional data could provide important evidence.

In concert with the change in aerobic power, fat free mass has also been shown to decline with increasing age (Borkan, Hults, Gerzof, Robbin & Silbert, 1983; Jackson, Beard, Wier, Ross, Stuteville & Blair, 1995; Jackson, Wier, Ayers, Beard, Stuteville & Blair, 1996; Neder, Nery, Silva, Andreoni & Whip, 1999; Tzankoff & Norris, 1977; Rice, Cunningham, Paterson & Lefcoe, 1989). Souminen, Heikkinnen, Liesen, Michel and Hollmann (1977) reported a slow decline in metabolically active tissue mass in older men and women over a 5-year period.

Davies *et al.* (1995) identified a negative relationship between lean body mass and age in their study of 73 older men. Similar findings have also been reported by Toth, Gardner, Ades and Poehlman (1994). Maximal oxygen uptake is influenced by the amount of metabolically active lean tissue (Cardus *et al.*, 1998). Therefore, to investigate meaningfully the tissue-specific decline in age-related $\dot{V}O_{2\,max}$, the influence of body size needs to be 'partitioned out'. Such partitioning out is called scaling (Schmidt-Nielsen, 1975). Traditionally, differences in body size have been scaled by the construction of ratio standards in which $\dot{V}O_{2\,max}$ is simply divided by body mass and expressed as $ml \cdot kg^{-1} \cdot min^{-1}$. The use of these ratio standards has been shown to be inappropriate (Batterham *et al.*, 1997; Katch, 1972, 1973; Katch & Katch, 1974; Nevill *et al.*, 1992; Packard & Boardman, 1987; Tanner, 1949; Vanderburgh *et al.*, 1996 & Winter, 1992) and, as demonstrated in the previous two studies, can distort the data leading to serious misinterpretation. No study has yet explored the age-related decline on $\dot{V}O_{2\,max}$ in older humans using non-linear allometric modelling.

As well as body size, $\dot{V}O_{2\,max}$ is also influenced by level of participation and intensity of physical activity (Fitzgerald, Tanaka, Tran & Seals, 1997; Jackson *et al.*, 1995, 1996; Talbot, Metter, & Fleg, 2000), both of which also tend to decline with advancing age (Cunningham, Paterson, Koval & St Croix, 1997). Thus, any estimation of the age-related decline in $\dot{V}O_{2\,max}$ could, in part, be accounted for by a reduction in participation and/or intensity of physical activity. Therefore, the scaling model used to estimate the tissue-specific age-related decline in $\dot{V}O_{2\,max}$ should also incorporate some appropriate measure of physical activity.

The purpose of this study was to use allometric modelling to explore the age-related decline in $\dot{V}O_{2\,max}$ independent of body size and physical activity in men and women in the 6th through 9th decades of life.

METHODS

Participants

The sampling frame was the non-institutionalised population aged 55 to 86 years living in the city of London Ontario, Canada in 1987 (total population of the city was 280,000). Institutions were nursing homes or chronic care facilities. The subject pool was provided from the municipal tax assessment list that contained all households and their inhabitants. A stratified random sample was drawn in which strata were defined by sex and six 5-year age groups starting with age 55. The sampling rate was set to select 35 men and women in each stratum. The initial telephone screening used the self-paced walking test (Cunningham, Rechnitzer, Pearce & Donner, 1982) over an 80 m course as the criterion for inclusion. An in-depth sampling frame description can be found in an earlier paper by Koval, Ecclestone, Paterson, Brown, Cunningham and Rechnitzer (1992).

The study was performed according to the Declaration of Helsinki and the University of Western Ontario Review Board for Health Sciences Research involving Human Subjects provided approval for the study. Prior to participation in this study, all subjects were given a thorough medical examination and provided written informed consent.

Anthropometry

Body mass (BM) was assessed to the nearest 0.1 kg using calibrated lever-balance scales (Health-O-Meter) and stature measured using a stadiometer (Holtain Harpenden) to the nearest 0.1 cm with the subject standing, lightly clothed and without footwear. Following guidelines set by Weiner & Lourie (1981), body density was estimated from the logarithm of the sum of four skin-fold measurements (Durnin & Womersley, 1974) and percentage body fat and subsequent fat free mass estimated using Siri's (1961) equation.

Physical activity

The physical activity of the participants in this study was assessed by the Minnesota Leisure Time Physical Activity (MLTA) questionnaire (Taylor, Jacobs, Schucker, Knudsen, Leon & Debacker, 1978). Initially, each subject completed the questionnaire on their own, based on the activities they had performed in the past year. This was then verified by a trained interviewer by recording detailed information on subjects' activities including specific months, the number of occasions in each month, and the duration of each occasion in which the activities were performed. In constructing the original questionnaire the level of intensity for each activity was derived from subjects aged 30 - 50 years. To reflect the older population in this study, the level of intensity was reduced in line with the recommendation of Himann, Cunningham, Rechnitzer and Paterson (1988), since it is likely that older subjects participating in similar activities to younger subjects would do so at a reduced absolute intensity. The activities listed in the questionnaire are classified by intensity as light, moderate and heavy. Only the heavy intensity activity scores were included in the analysis since they should theoretically provide the greatest cardiorespiratory stimulus. A more detailed account of the procedures used in collecting the physical activity data has been published by Amara, Koval, Johnson, Paterson, Winter and Cunningham (2000).

Maximal oxygen uptake

Maximal oxygen uptake was determined during a continuous incremental walking test to volitional exhaustion or symptom-limited fatigue on a motorised treadmill. Ventilatory volume was measured with a bi-directional turbine and volume transducer (SensorMedics VMM-2A), which were calibrated daily with a syringe of known volume (3.0 litres). Sampled expirate was analysed by mass spectrometer (Perkin-Elmir MGA-110), which was calibrated daily with precision-analysed gas mixtures. A more detailed account of these methods has been published by Cunningham *et al.* (1997).

Using criteria for older subjects developed by Cunningham, Rechnitzer, Howard and Donner (1987), $\dot{V}O_{2\,max}$ was considered to have been attained if one of the following was achieved: (a) a feeling of fatigue and a 15-second plateau in oxygen uptake concurrent with an increase in the intensity of exercise; (b) a respiratory exchange ratio > 1.0, and a heart rate within 5 $b{\cdot}min^{-1}$ of estimated maximum (HR_{max} = 220 – age). Of the 441 subjects who took part in the study, 298 subjects (152 men, 146 women) satisfied one or both of the above criteria and were considered to have reached $\dot{V}O_{2\,max}$ (72 % with a plateau).

Statistical analyses

All analyses were carried out using SPSS version 9 (SPSS Inc., Chicago, IL). Descriptive statistics were performed on the summary data. Using graph plots and bivariate correlation, preliminary analyses were made of the relationship between $\dot{V}O_{2\,max}$, physical activity, body mass and fat free mass with increasing age in both the men and women. The following models were used to evaluate $\dot{V}O_{2\,max}$:

1. The influence of age and body mass (or FFM) on $\dot{V}O_{2\,max}$ was investigated using the allometric model proposed by Nevill & Holder (1995). The influence of sex was also investigated, producing a model of the form:

$$\dot{V}O_{2\,max} = BM^{b} \cdot \exp(a + c \cdot age + d \cdot age^2 + f \cdot sex) \in$$

where sex is coded '0' for women and '1' for men and $\in$ represents a random multiplicative error term, in the model body mass can be replaced by fat free mass. The model was linearised by taking the natural logarithm (*ln*) of $\dot{V}O_{2\,max}$ and body mass (or FFM). Hence:

$$ln\,\dot{V}O_{2\,max} = b \cdot lnBM + a + c \cdot age + d \cdot age^2 + f \cdot sex + ln\in$$

To confirm that men and women could be compared using the same body size scaling exponent, the homogeneity of the body mass (or FFM) coefficient was first verified by including a $sex \times lnBM$ (or *ln*FFM) variable into the linearised model to check for interaction. Following this, coefficients *a*, *b*, *c* and *d* were estimated using standard multiple regression.

2. The influence of physical activity was investigated using an allometric model. However, statistical and physiological justification is required to support the incorporation of physical activity, namely, is the relationship between physical activity and $\dot{V}O_{2\,max}$ linear or curvilinear? It is well documented that physical activity at the correct intensity is positively related to $\dot{V}O_{2\,max}$. However as illustrated in Figure 6·1, there comes a point when an increase in physical activity results in little or no gain in $\dot{V}O_{2\,max}$, at this point $\dot{V}O_{2\,max}$ is said to have reached a plateau. Therefore, the relationship between physical activity and change in $\dot{V}O_{2\,max}$ must be curvilinear.

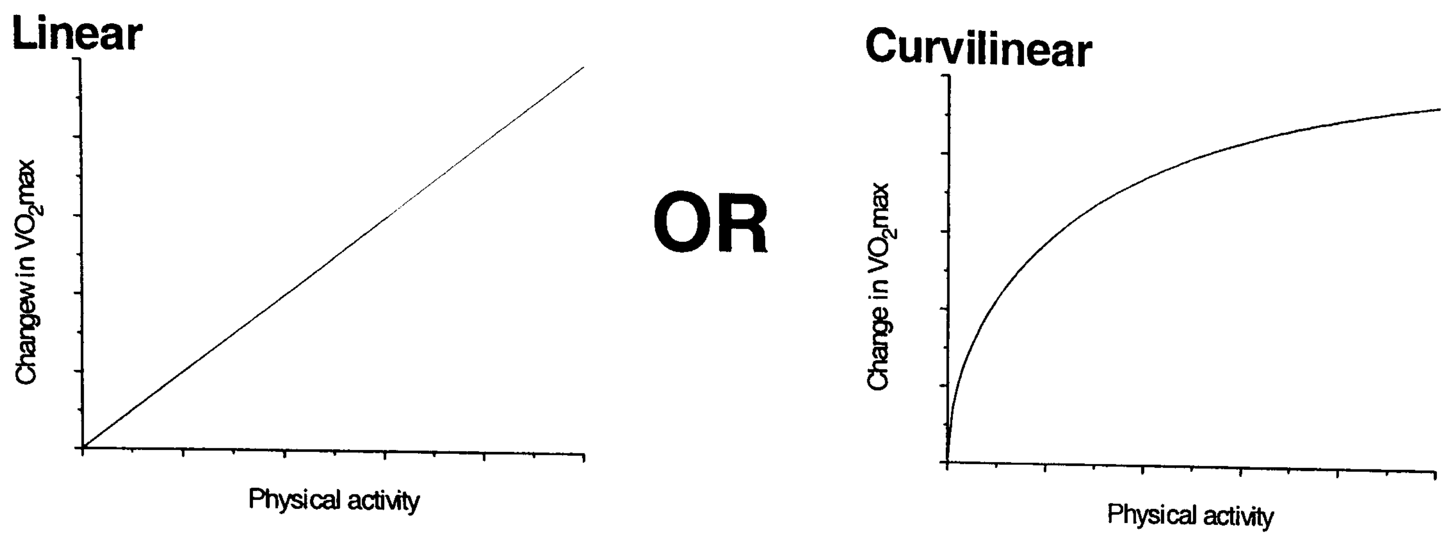

Figure 6·1: Illustration of the relationship between maximal oxygen uptake and physical activity.

Incorporating physical activity as a curvilinear variable produced the following allometric model:

$$\dot{V}O_{2\,max} = BM^{b} \cdot PA^{g} \exp(a + c \cdot age + d \cdot age^{2} + f \cdot sex) \in$$

The model was linearised by taking the natural logarithm (*ln*) of $\dot{V}O_{2\,max}$, body mass (or FFM) and physical activity (PA). To confirm that men and women could be compared using the same body size and physical activity scaling exponents, the homogeneity of the coefficients was first verified by including *sex* × *ln*BM (or *ln*FFM) and *sex* × *ln*PA variables into the linearised model to check for interaction. Following this verification, coefficients were identified using standard multiple regression.

Regression diagnostics

Homogeneity of variance between the male and female data was checked using the procedures recommended by Snedecor & Cochran (1980). The

Kolmogorov-Smirnov test using Lilliefors significance correction was used to check that the residuals about regression were normally distributed and an additive error structure confirmed by correlating the absolute residuals from the logged model with *ln*BM and *ln*FFM. Significance level was set at $p < 0.05$.

Checks for collinearity were made using tolerance and variance inflation factors (VIF) for each of the predictor variables calculated by means of the collinearity diagnostics in SPSS.

RESULTS

Descriptive and physiological data for the men and women are presented in Table 6·1. There was no evidence of a gender difference in age ($p = 0.170$) or physical activity ($p = 0.801$), and not surprisingly, the men were heavier, leaner and had a higher absolute $\dot{V}O_{2\,max}$ than the women ($p < 0.001$).

Decline in $\dot{V}O_{2\,max}$ with age is clearly evident in Figure 6·2, with correlation coefficients of -0.611 and -0.596 for the men and women respectively ($p < 0.001$). Figure 6·3a shows that in the men there was also a decline in body mass with increasing age ($R = -0.368$, $p < 0.001$). A similar trend, as shown in Figure 6·3b, applied when body mass was replaced with fat free mass ($R = -0.286$, $p < 0.001$). Physical activity was also found to decline with age in the women ($R = -0.187$, $p = 0.024$) but no change was found in the men ($R = -0.122$, $p = 0.134$).

Table 6·1: Summary data for men and women (mean ± SD).

	Men ($n = 152$)	Women ($n = 146$)	t	p
Age (years)	68.7 ± 8.1	70.0 ± 8.1	-1.4	0.170
Body mass (kg)	78.2 ± 10.6	63.8 ± 10.1	12.0	< 0.001
Body fat (%)*	24.7 ± 4.5	35.8 ± 4.4	-21.3	< 0.001
Fat free mass (kg)**	58.4 ± 6.3	40.6 ± 4.8	27.0	< 0.001
$\dot{V}O_{2\,max}$ ($l \cdot min^{-1}$)	1.78 ± 0.46	1.21 ± 0.25	13.4	< 0.001
Physical activity ($METS \cdot year^{-1}$)*	77.7 ± 118.6	81.3 ± 127.2	0.3	0.801

Owing to missing values: **Men ($n = 150$) and Women ($n = 141$), *Men ($n = 151$).

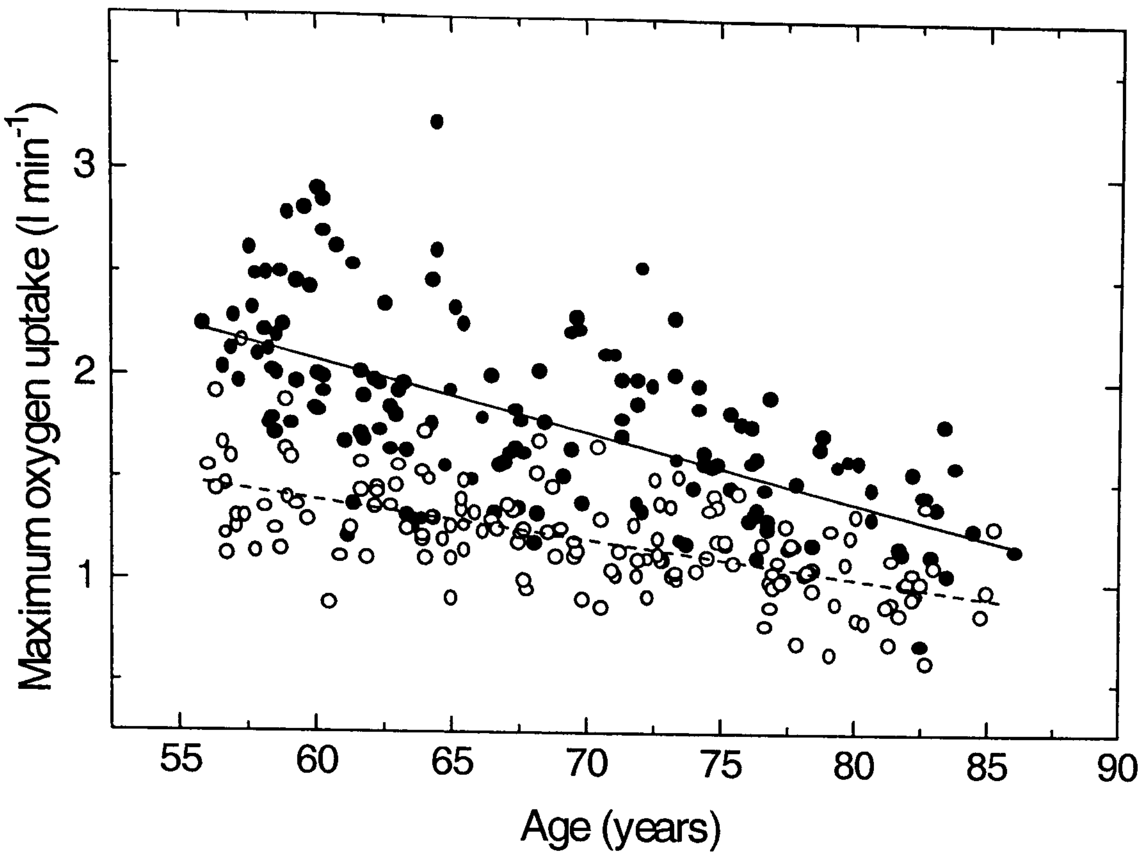

Figure 6·2: Decline in $\dot{V}O_{2\,max}$ with age in older men (•) and women (○).

Body mass model

1. There was no evidence of a *sex* × *ln*BM interaction (t = 1.60, p = 0.110) and thus this variable was removed from the model. This confirms the homogeneity of slopes between men and women and justifies the analysis of the data using the same body mass scaling exponent (b). Subsequent analysis revealed no effect of the quadratic *age* variable, age^2 (t = 0.09, p = 0.932), and was also removed from the model. Multiple regression explained 68.8 % (R = 0.829, SEE = 0.170) of the variability in $\dot{V}O_{2\,max}$. Individual β-coefficients (± SEE) for *ln*BM (0.563 ± 0.070), *age* (-0.0154 ± 0.0012) and *sex* (0.242 ± 0.024) were all significant (p < 0.001) and incorporated into the model so producing an expression of the form:

$$ln\,\dot{V}O_{2\,max} = 0.5636 \cdot ln\mathrm{BM} - 1.09 - 0.01546 \cdot \mathrm{age} + 0.2426 \cdot \mathrm{sex} + ln\epsilon$$

By taking the antilogarithm of $ln\,\dot{V}O_{2\,max}$ and lnBM the following allometric model was derived:

$$\dot{V}O_{2\,max} = BM^{0.563}\, \exp(-1.09 - 0.01546 \cdot age + 0.2426 \cdot sex) \in$$

As illustrated in Figure 6·4a, the model estimates the age-associated decline in $\dot{V}O_{2\,max}$ independent of changes in body mass as 1.5 % per year ($e^{-0.0154 \cdot age}$).

2. Further to introducing physical activity into the model, there was no evidence of a $sex \times ln$PA ($t = 0.04, p = 0.970$) or $sex \times ln$BM interactions ($t = 1.88, p = 0.061$) and these variables were removed from the model. Subsequent analysis revealed no effect of the quadratic age variable, age^2 ($t = 0.42, p = 0.672$), and this was also removed from the model. Multiple regression explained 70.4 % ($R = 0.839$, SEE = 0.169) of the variability in $\dot{V}O_{2\,max}$ and identified individual β-coefficients (± SEE) for lnBM ($0.579 \pm 0.071, p < 0.001$), *age* ($-0.0145 \pm 0.0013, p < 0.001$), *sex* ($0.250 \pm 0.025, p < 0.001$) and physical activity ($0.0197 \pm 0.0075, p < 0.009$). By exponentiating $ln\,\dot{V}O_{2\,max}$ and lnBM the following allometric model was derived:

$$\dot{V}O_{2\,max} = BM^{0.579} \cdot PA^{0.0197} \cdot \exp(-1.29 - 0.0145 \cdot age + 0.250 \cdot sex) \in$$

This model estimates the age-associated decline in $\dot{V}O_{2\,max}$ independent of changes in body mass and physical activity as 1.4 % per year ($e^{-0.0145 \cdot age.}$).

Fat free mass model

1. There was no evidence of a $sex \times ln$FFM interaction ($t = 1.65, p = 0.100$), so confirming the homogeneity of slopes between men and women and thus this variable was removed from the model. Subsequent analysis revealed no effect of

the quadratic age variable, age^2 ($t = 0.370, p = 0.712$), and this was also removed from the model. Multiple regression explained 69.2 % ($R = 0.832$, SEE = 0.167) of the variability in $\dot{V}O_{2\,max}$. Individual β-coefficients (± SEE) for *ln*FFM (0.772 ± 0.090) and *age* (-0.0159 ± 0.0012) were significant at $p < 0.001$ with *sex* (0.077 ± 0.038) only just significant ($p = 0.049$). By taking the antilogarithm of $ln\,\dot{V}O_{2\,max}$ and *ln*FFM the following allometric model was derived:

$$\dot{V}O_{2\,max} = FFM^{0.772}\exp(-1.57 - 0.0159\cdot age + 0.077\cdot sex)\,\in$$

Independent of changes in fat free mass, this model estimates the age-associated decline in $\dot{V}O_{2\,max}$ independent of changes in fat free mass as 1.6 % per year ($e^{-0.0159\cdot age.}$), see Figure 6·4b for illustration.

2. Further to introducing physical activity into the model, there was no evidence of a $sex \times ln$PA ($t = 0.04, p = 0.970$) and so this was removed from the model. With the inclusion of physical activity, *sex* was no longer found to be significant ($t = 1.502, p = 0.134$) negating the need to check for a $sex \times ln$FFM interaction. Accordingly, both variables were removed from the model. The quadratic age variable, age^2, was again found not to be significant ($t = 1.05, p = 0.296$), and was also removed from the model. Multiple regression explained 70.7 % (R = 0.841, SEE = 0.166) of the variability in $\dot{V}O_{2\,max}$ and individual β-coefficients (± SEE) were estimated for *ln*FFM (0.957 ± 0.048, $p < 0.001$), *age* (-0.0148 ± 0.0013, $p < 0.001$) and physical activity (0.0209 ± 0.0075, $p < 0.006$). By exponentiating $ln\,\dot{V}O_{2\,max}$ and *ln*FFM the following allometric model was derived:

$$\dot{V}O_{2\,max} = FFM^{0.972} \cdot PA^{0.0209} \cdot \exp(-2.40 - 0.0148 \cdot age) \cdot \in$$

As illustrated in Figure 6·4c, this model estimates the age-associated decline in $\dot{V}O_{2\,max}$ independent of changes in fat free mass and physical activity as 1.5 % per year ($e^{-0.0148 \cdot age}$).

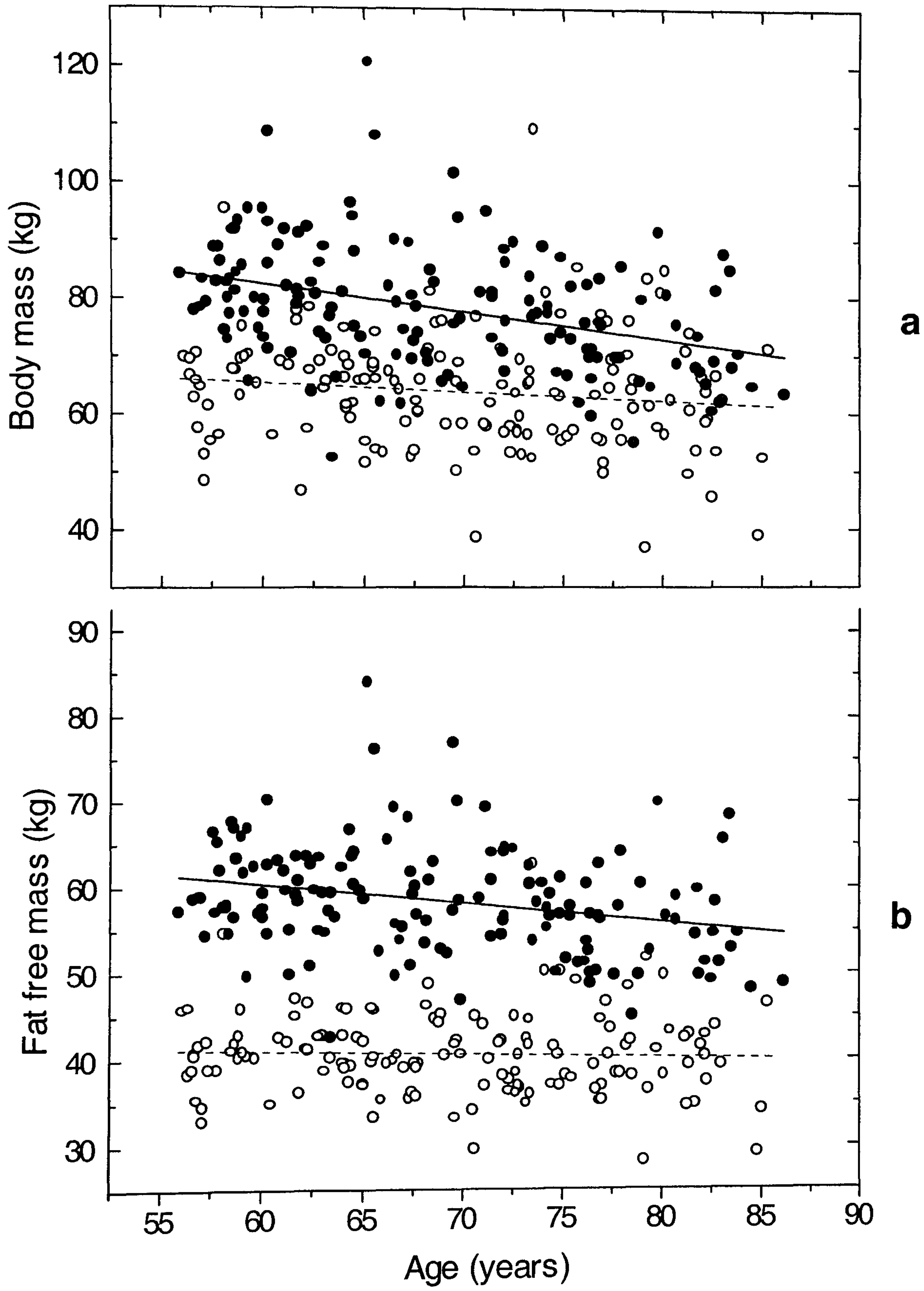

Figure 6·3: Body mass (**a**) and fat free mass (**b**) as a function of age in independent older men (●) and women (○).

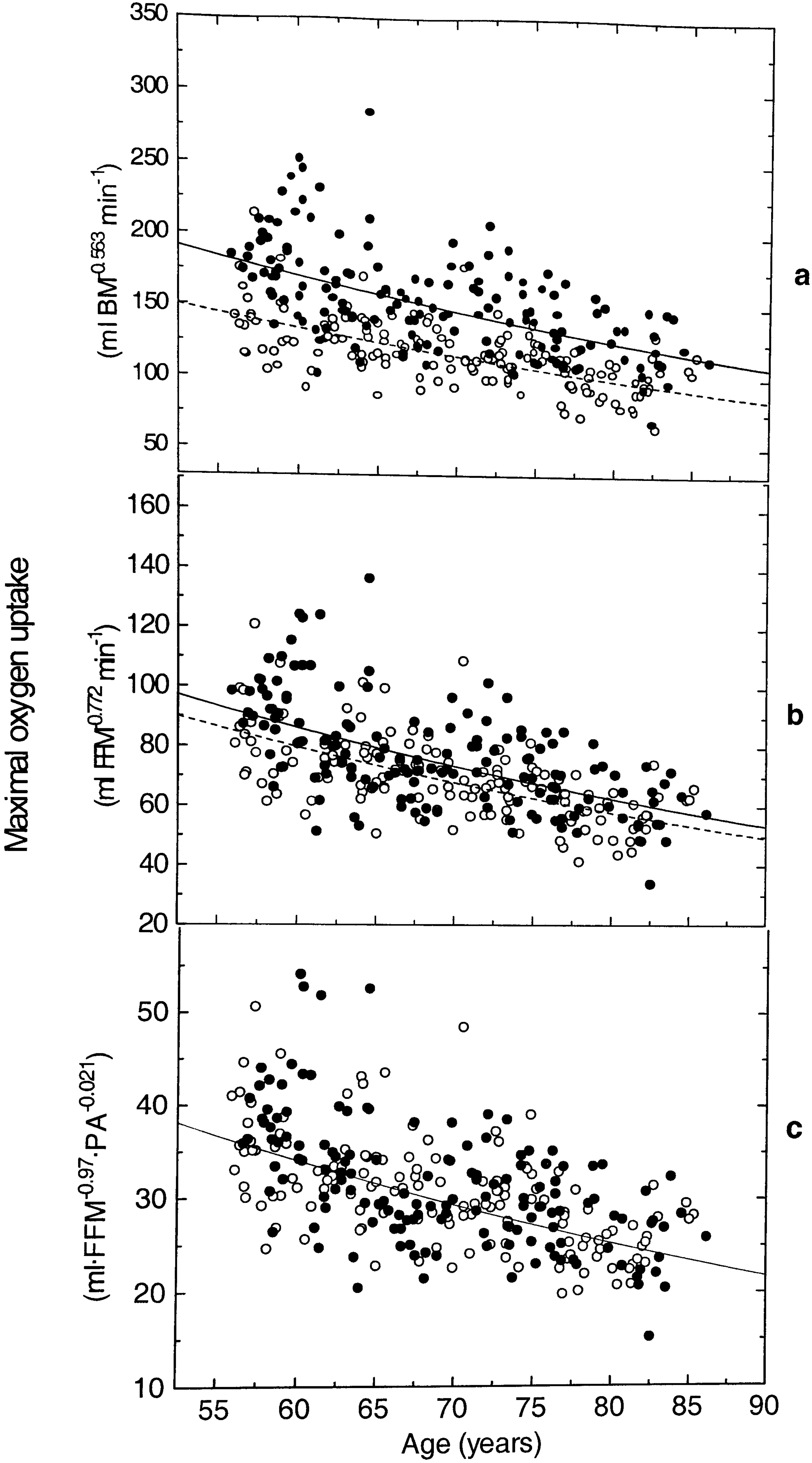

Figure 6·4: Age-associated decline in $\dot{V}O_{2\,max}$ independent of body mass (**a**), fat free mass (**b**) and fat free mass & physical activity (**c**) in older men (●) and women (O).

Regression Diagnostics

Homogeneity of variance for the allometric models was confirmed ($p >$ 0.10). In all models, no relationship ($p > 0.05$) was found between the absolute residuals and predictor variables (*ln*BM, *ln*FFM, *ln*PA & *age*) and, as illustrated in Figure 6·4, the residuals from all models were normally distributed ($p > 0.20$). Both these checks indicate that the data had been correctly treated and confirmed the appropriateness of the logarithmic transformation.

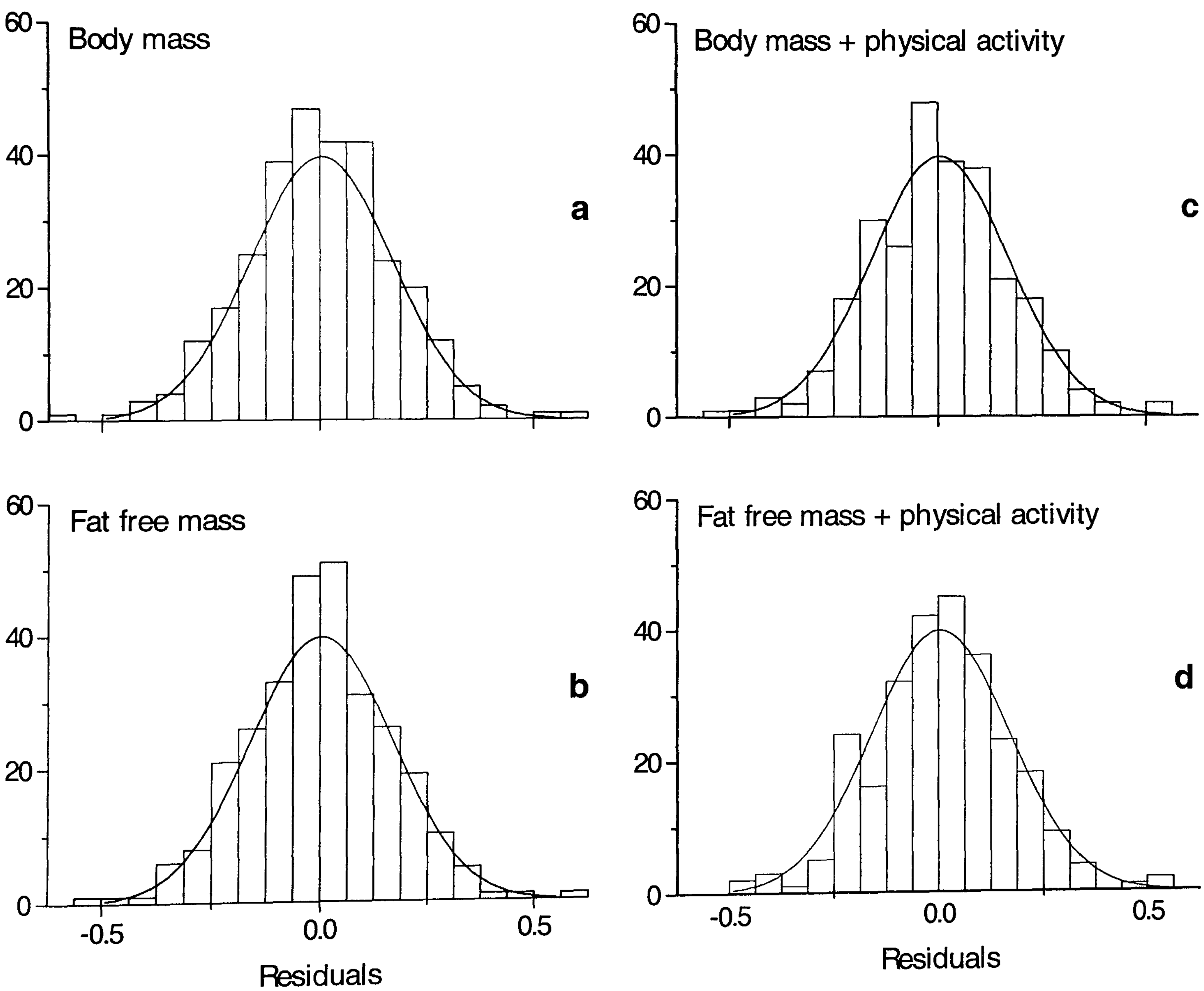

Figure 6·5: Distribution of residuals from the body mass (**a**), fat free mass (**b**), body mass & physical activity (**c**) and fat free mass & physical activity models (**d**).

In both body mass models, VIF (variance inflation factor) and tolerance values were close to 1 indicating little evidence of collinearity. In the fat free mass model (without physical activity), the tolerance and VIF values for *ln*FFM (3.83 & 0.261, respectively) and *sex* (3.77 & 0.267, respectively) indicated moderate influence of collinearity between *ln*FFM and *sex* and possible redundancy of either variable. With the introduction of physical activity into the fat free mass model, *sex* was no longer a significant predictor and further to its removal no evidence of collinearity was found.

DISCUSSION

In common with others, this study has shown a decline in $\dot{V}O_{2\,max}$ with increasing age. This study has also identified a decline in body mass and fat free mass in older men but not in the women. Dependent on choice of model, the age-associated decline in $\dot{V}O_{2\,max}$, independent of changes in body mass or fat free mass, was estimated at ≈ 1.5 % per year in both the men and women which, due to the exponential nature of the estimate, equates to ≈ 14 % per decade, as illustrated in Table 6·2. Moreover, this multiplicative *age* factor means that estimates are relative to a subject's current age, sex, body size and level of physical activity. The relative nature of these estimates makes it impossible to compare the lower absolute values previously reported to be around 10 % per decade (Buskirk & Hodgson 1987; Dill, Robinson & Ross, 1967 & Rogers, Hagberg, Martin III, Ehsani & Holloszy, 1990). These absolute estimates erroneously predict the same loss in $\dot{V}O_{2\,max}$ regardless of age, level of physical activity, current level of $\dot{V}O_{2\,max}$ and age-related changes in body size.

As illustrated in Table 6·2, the use of either body mass or fat free mass as the body size variable gives estimates similar to the age-associated decline in $\dot{V}O_{2\,max}$. Even the introduction of physical activity had little effect. Moreover, all models accounted for similar variability in the between-subject differences in $\dot{V}O_{2\,max}$ of around 70 %. However, with the introduction of physical activity into the fat free mass model, gender was no longer significant ($p = 0.134$) and removed from the model. This inferred that after accounting for differences in body size, fat mass, age and physical activity, older men and women have similar $\dot{V}O_{2\,max}$. This parity between older men and women was indicated by the presence of collinearity in the fat free mass model. The problem was due to fat free mass accounting for most of the variability explained by *sex*, indicating possible redundancy of the *sex* variable. With the introduction of physical activity and subsequent deletion of the *sex* variable any evidence of collinearity disappeared.

Table 6·2: Predicted age-associated decline in maximal oxygen uptake after 1 and 10 years (± 95 % confidence intervals).

	Age-associated decline in $\dot{V}O_{2\,max}$	
	1 year	10 years
Body mass model:		
Body mass	1.5 % (1.3, 1.8)	14.3 % (12.2, 16.3)
Body mass & physical activity	1.4 % (1.2, 1.7)	13.5 % (11.3, 15.7)
Fat free mass model:		
Fat free mass	1.6 % (1.3, 1.8)	14.7 % (12.7, 16.7)
Fat free mass & physical activity	1.5 % (1.2, 1.7)	13.8 % (11.5, 15.9)

As discussed previously in studies **1** and **2**, body mass as the body size variable fails to account for gender differences in body composition thus depending on the *sex* variable to account, in part, for this lack of sensitivity. Hence from both a physiological and statistical standpoint, fat free mass should always be used in preference to body mass. However, a caveat to this conclusion is the accuracy of the measurement of body fat percentage, which is used to calculate fat free mass. Body density was estimated using Durnin & Wormersley's (1974) algorithm which was based on subjects aged 50 to 72, and, as such, might not be as valid in subjects aged 72 plus. For practical reasons, more elaborate determination of muscle mass, such as magnetic resonance imaging or computerised axial tomography, was not possible although they should be considered for future investigation.

Using the model proposed by Nevill and Holder (1995), the influence of age was initially investigated using a quadratic function (*age* & age^2). From a physiological basis this seems logical as the aerobic quality of the muscle develops in the young and, as illustrated in Study **2**, tends to peak in a persons 20's and thereafter decline with advancing age. However, in all models the variable age^2 was not significant ($p > 0.30$) and subsequently removed. On reflection the age range of this sample (55 - 86) was towards the right hand side (tail) of the quadratic function thus having little curvature, meaning that the age^2 parameter became redundant as it added little or no information. The age-associated decline in $\dot{V}O_{2\,max}$ in older humans was best estimated with a linear term, albeit on the log scale.

The age-associated decline in body mass and fat free mass in men identified in this study was also reported by Toth *et al.* (1994) and Davies *et al.* (1995). Possible mechanisms are age-related changes in the anabolic hormone testosterone and human growth hormone which influence the amount and make-up of active tissue (Rudman, Feller, Nagraj, Gergans, Lalitha, Goldberg, Schlenker, Cohen, Rudman & Mattson, 1990; Rudman, Feller, Cohn, Shetty, Rudman & Draper, 1991). Human growth hormone secretion declines after the age of 40, especially in men (Isaksson, Eden & Jansson, 1985). Testosterone levels in men also decline with advancing age (Gray, Feldman, McKinlay & Longcope, 1991; Proctor, Balagopal & Nair, 1998) and this decline has been shown to be mirrored by a loss of lean body mass and muscular strength (Balagopal, Rooyackers, Adey, Ades & Nair, 1997; Larsson & Karlsson 1978). Older women do not experience such a change in anabolic steroids and growth hormone with advancing age (Isaksson *et al.*, 1985) and thus tend not to experience such a decline in body mass and fat free mass.

Independent of changes in body size and physical activity, the age-associated decline in $\dot{V}O_{2\,max}$ can be attributed to a number of factors. Most important is the loss of oxidative capacity due to changes in the muscle structure. These have been explored in several studies (McCully, Fielding, Evans, Leigh & Posner, 1993; Ozawa, 1997). They have shown a reduced respiratory chain enzyme and oxidative phosphorylation rate in the elderly. In addition, mitochondrial volume density could also be lower in the elderly further reducing the oxidative capacity of the tissues. However, as found in this study, the continuing participation in regular physical activity will do much to retard this decline in aerobic function. For example, participation in 80 METs of physical activity per year (mean value from this population) would see, on average, an increase in aerobic function of 9.6% ($800^{0.209}$) over a sedentary lifestyle.

Non-linear allometric modelling has been demonstrated to be a superior scaling alternative to traditional techniques (Bergh, 1987; Bergh *et al.*, 1991; Davies *et al.*, 1995; Nevill, *et al.*, 1992; Winter, 1992). This is especially so when differences or changes in body size are marked (Winter, 1992) such as found when investigating growth in children (Armstrong, Welsman, Nevill & Kirby, 1999; Rowland *et al.*, 1987; Welsman *et al.*, 1996). Likewise, in a later period of life where body size tends to decline, this study has successfully used non-linear allometric modeling to investigate the age-associated decline in $\dot{V}O_{2\,max}$.

Chapter 7

STUDY 4

Modeling sub-maximal oxygen uptake in male and female distance-runners.

INTRODUCTION

Success in middle- and long-distance running has been attributed '...primarily to the athlete's ability to consume oxygen maximally' (Conley & Krahenbuhl, 1980). As female distance-runners tend to exhibit a lower maximal oxygen uptake ($\dot{V}O_{2\,max}$), per given unit of body mass, than their male counterparts (Padilla *et al.*, 1992; Wilmore & Brown, 1974), this difference has been attributed in some part to their inferior running performance.

More recently, running economy has been found to be a better indicator of performance than $\dot{V}O_{2\,max}$ (Conley & Krahenbuhl, 1980; Costill, Fink, Flynn & Kirwan, 1987), especially in homogeneous groups of runners (Daniels & Daniels, 1992). However, of the numerous studies that have investigated the gender differences in running economy, conflicting results have been reported. One problem in comparison is the sex-specific difference in body fat. Cureton and Sparling (1980) attempted to account for this gender difference by adding excess weight to the men '...so that the total percent excess weight was equal to the % fat of a matched female' (*p*. 288). The authors still identified a gender difference in running economy, although the difference between the men and women decreased.

In all the above studies, no attempt was made to investigate the relationship between body size and $\dot{V}O_2$ at the measured running speed. As demonstrated in the previous three studies, the nature of this relationship is paramount in determining expressions of $\dot{V}O_{2\,max}$ independent of body size. Only then can meaningful gender comparison be made. The three previous studies found that a body size exponent of less than one was appropriate in scaling values for $\dot{V}O_{2\,max}$. If sub-maximal $\dot{V}O_2$ is influenced by body size in the same way as $\dot{V}O_{2\,max}$, then the use of the ratio standard (ml·kg^{-1}·min^{-1}) will over estimate the influence of body size and 'over-scale' the data. This 'over-scaling' will tend to inflate values of $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) for the lighter runners and under-estimate values for the heavier runners. Such distortion will cloud interpretation and can even create artificial differences between groups, especially when differences in body size are large, as in comparisons of men and women or children and adults.

Guidelines for assessing, interpreting and comparing running economy have recently been published in the document Physiological Support to UK Athletics (Jones, 2000). For World-class performers, it is suggested that running economy should be assessed at 16 km·hour^{-1} and a standard is set of 52 ml·kg^{-1}·min^{-1}. Below this standard, recommendations are made to adjust an athlete's training program with more emphasis on longer and slower training sessions to improve their running economy. However, the standard used has been calculated using the ratio standard, which has been shown to be inappropriate and to cause distortion. This distortion could lead an investigator to incorrectly assess an athlete's running economy and to recommend unsuitable changes in their training program.

Earlier attempts to assess standards for running economy, or as termed the 'energy cost of running', have been published (di Prampero, 1986 & Margaria, Cerretelli, Aghemo & Sassi, 1963). However, these have been also constructed using the ratio standards and should be used with caution.

Comparisons of sub-maximal oxygen uptake using non-linear allometric modeling have been published by Davies, Mahar and Cunningham (1997), Bergh *et al.* (1991), and Rogers *et al.* (1995). Davies *et al.* (1997) in their comparison of running economy in 12 male and 12 female distance-runners identified a pooled body mass exponent of 1.01. This justified the use of the ratio standard to remove the influence of body mass and identified no gender difference in running economy. However, they only assessed running economy at one running speed (3.58 $m \cdot s^{-1}$) and did not investigate the possible influence of gender differences in body composition. Bergh *et al.* (1991) investigated the relationship between body mass and $\dot{V}O_2$, identifying a body mass exponent of 0.76, but made no gender comparison. Rogers *et al.* (1995) restricted their investigation to differences between adults and children. No study has yet investigated the influence of body size and body composition on sub-maximal $\dot{V}O_2$ in men and women using allometric modelling.

Therefore, the purpose of this study was to investigate the relationship between body size, body composition and sub-maximal $\dot{V}O_2$ in male and female distance runners and make meaningful gender comparison.

METHODS

Participants

Thirty-four middle- and long-distance runners (17 male, 17 female) were recruited from running clubs in the South East of England. Participants were selected using the following criteria:

- age: between 16 - 35 years old
- experience: minimum of three years
- training status: currently in full training and free from injury

All participants were given written details of the procedures to be used and they provided written informed consent (see Appendix 7·1).

General procedures

All testing took place in the Physiology of Exercise Laboratories at De Montfort University, Bedford, and conducted in accordance with the guidelines laid down by the British Association of Sport and Exercise Sciences (Bird & Davidson, 1997). Further to an initial visit to habituate the participant to treadmill running, expired air collection and other experimental procedures; participants' $\dot{V}O_2$ was assessed at four sub-maximal running speeds (2.72, 3.17, 3.61 & 4.05 $m \cdot s^{-1}$). Due to the confounding influence of the slow component, it was confirmed that subjects were exercising below their anaerobic threshold (respiratory exchange ratio < 1.0), for all running speeds. All tests took place at times when the participants would have normally trained and participants were instructed to have refrained from exercise for at least 24 hours (>48 hours hard training) and be at least 2 hours post absorptive. Ambient laboratory temperature was maintained throughout at 20°C (±

2), controlled by Mitsubishi (Mr Slim) air conditioning unit. Humidity, although not controlled, ranged from 15 to 52%. Reproducibility of all measurements was checked before data collection and calibration of equipment took place prior, during and post testing, the relevant details can be found in Chapter 3. In particular, in an effort to ensure that all participants exercised at the same four running speeds, the same treadmill was always used, which was regularly calibrated (see Appendix 3·4).

Mass and stature

Measurement of mass and stature were made in accordance with the guidelines laid down by Lohman, Roche and Martorell (1988). Stature was measured to the nearest 0.001 m, using a Holtain Harpenden stadiometer, and body mass measured to the nearest 0.05 kg, using Seca (model 713) beam scales, immediately prior to testing.

Body composition

Following the guidelines set by Weiner and Lourie (1981), skin-fold measurements were made using Holtain calipers on the left side of the body over the biceps, triceps, sub-scapula and suprailiac. Three measurements were made at each site; the mean of the closest two values was used. Taking the logarithm of the sum of the skin-fold measurements, body density was estimated using the equations described by Durnin and Womersley (1974) and percentage body fat calculated from the formula of Siri (1961). Fat mass and fat-free mass (FFM) constituents were then calculated. To minimise the error normally associated with this measurement, inter and between-investigator reproducibility had been assessed and the same calipers were always used. They had been calibrated with weights following the instructions given by Weiner and Lourie (1981).

Sub-maximal oxygen uptake

Oxygen uptake was determined by the open circuit method during a continuous incremental treadmill run (Powerjog, M30) at four sub-maximal running speeds; 2.72, 3.17, 3.61 and 4.05 $m \cdot s^{-1}$. After a five-minute warm-up and flushing out of the connecting tubes with the participant's expirate, each participant ran for four minutes at each running speed. For the last minute of each speed, expired air was collected, in sequence with pulmonary cycles, for a time interval that approximated 60-seconds, measured accurately to the nearest one-hundredth second by an electronic bag-timing system and BBC Micro (8000) computer and software. The expired air was collected, via a low-resistance Salford breathing valve and Falconia tubing, in 150 litre Douglas bags with Rudolph 2700 two way valves. The expirate was condensed, and O_2 and CO_2 fractions determined using a Servomex 1490 infrared (CO_2) analyser and a Servomex 1100 paramagnetic oxygen transducer. Expirate volume was determined by first drawing the expirate through a drying agent (silica crystals) and then measured by a Harvard dry gas meter. Temperature of expirate was measured from the exit area of the gas meter. Prior to testing three electrodes were attached to the participant in a modified V_5 formation and connected to an ECG to monitor heart rate.

Analyses

All analyses were made using SPSS version 9 (SPSS Inc., Chicago, IL). Descriptive statistics were performed on the summary data and preliminary analyses of the relationship between body mass and fat-free mass with $\dot{V}O_2$ were made using bivariate correlation. The following models were used to express $\dot{V}O_2$:

1. Ratio standard, constructed by dividing values for $\dot{V}O_2$ ($ml \cdot min^{-1}$) by body mass and expressed in $ml \cdot BM^{-1} \cdot min^{-1}$. Values compared using repeated measures analysis of variance (ANOVA). To confirm whether men and women could be compared using the same running speed parameter, the homogeneity of the running speed coefficient (slope) was first verified by including *sex* $\times$ *speed* variable to check for interaction.

2. Allometric model. Influence of body mass (or FFM) on $\dot{V}O_2$ was investigated using the allometric model proposed in Study 1, replacing $\dot{V}O_{2\,max}$ with $\dot{V}O_2$ ($l \cdot min^{-1}$) at a given running speed,

$$\dot{V}O_{2\,,\,speed} = \mathrm{BM}^{b} \text{ (or FFM}^{b}) \cdot \exp(a + c \cdot \mathrm{sex}) \cdot \epsilon$$

where *sex* is incorporated as a dummy variable (coded '0' for women and '1' for men) and ϵ represents a random multiplicative error term. The model was linearised by taking the natural logarithm (*ln*) of $\dot{V}O_2$ and body mass (or FFM). Hence:

$$ln\ \dot{V}O_{2\,,\,speed} = b \cdot ln\mathrm{BM} \text{ (or FFM)} + a + c \cdot \mathrm{sex} + ln\epsilon$$

To confirm whether men and women at the four running speeds could be compared using the same body size scaling exponent (*b*), the homogeneity of the body mass (or FFM) coefficient (slope) was first verified by including *sex* $\times$ *lnBM* (or lnFFM), *speed* $\times$ *lnBM* (or FFM) and *sex* $\times$ *speed* variables into the linearised model to check for interaction. Following this verification, the main effect of *speed* and covariates, *ln*BM and *sex*, were assessed using repeated measures ANCOVA. Further to these results, pooled estimates for *ln*BM, *sex* and *speed* where calculated following the guidelines by Snedecor & Cochran

(1984). Using these calculated pooled estimates, a generic running economy allometric model was fitted according to the model:

$$\dot{V}O_{2\,,\,speed} = BM^{b}\ (\text{or } FFM^{b})\cdot \exp(a\ + c\cdot \text{sex} + d\cdot \text{fat} + f\cdot \text{speed})\cdot \in$$

Power function values were then constructed by dividing $\dot{V}O_2$ (ml·min^{-1}) at each running speed by the pooled body mass (or FFM) scaling exponent and expressed in ml·BM^{-b} (or FFM^{-b})·min^{-1}.

3. Allometric model with fat mass. Systematic differences in body composition were also investigated by introducing fat mass (*fat*) into the allometric model. Taking the natural logarithm of $\dot{V}O_2$ and body mass (or FFM) produced a linear expression of the form:

$$ln\ \dot{V}O_{2\,,\,speed} = b\cdot ln\text{BM (or } ln\text{FFM)} + a + c\cdot \text{sex} + d\cdot \text{fat} + ln\in$$

Further to confirming that men and women could be compared using the same body size scaling exponent, *speed* and *fat* parameters, coefficients for running speed were identified using repeated measures ANCOVA. Pooled estimates were again calculated and used to fit the following generic running economy allometric model:

$$\dot{V}O_{2\,,\,speed} = BM^{b}\ (\text{or } FFM^{b})\cdot \exp(a\ + c\cdot \text{sex} + d\cdot \text{fat} + f\cdot \text{speed})\cdot \in$$

Power function values were then constructed by dividing $\dot{V}O_2$ (ml·min^{-1}) at each running speed by the pooled body mass (or FFM) scaling exponent and *fat* parameter and expressed in ml·BM^{-b} (or FFM^{-b})·exp(d·fat)·min^{-1}.

Model diagnostics

The Kolmogorov-Smirnov test using Lilliefors significance correction was used to check that the residuals about the regression fit were normally distributed and an additive error structure confirmed by correlating the absolute residuals from each model with the respective body size variable (BM, *ln*BM or *ln*FFM). Were appropriate, checks for collinearity were made using tolerance and variance inflation factors (VIF) for each of the predictor variables, calculated by means of the collinearity diagnostics in SPSS. Significance level was set at $p < 0.05$.

RESULTS

Descriptive and recruitment criteria data for the men and women were summarised and presented in Table 7·1, see Appendix 7·2 for individual data. There were no significant gender differences in age and training experience ($p = 0.947$ & 0.468, respectively) indicating similar groups in terms of recruitment criteria. Not surprisingly, the men were heavier, taller, had less body fat and a higher absolute $\dot{V}O_{2\,max}$ than the women ($p < 0.001$). Absolute values for oxygen uptake ($l \cdot min^{-1}$) for the men and women at all four running speeds are presented in Table 7·2; individual values are listed in Appendix 7·3. Gender comparison confirmed that the men had a higher absolute $\dot{V}O_2$ than the women ($p < 0.001$) at all running speeds.

Table 7·1: Summary data for men and women (mean ± SD).

	Men ($n = 17$)	Women ($n = 17$)	t	p
Age (years)	23.2 ± 4.6	23.4 ± 6.4	0.07	0.947
Experience (years)	7 ± 5	8 ± 4	0.73	0.468
Stature (m)	1.80 ± 0.07	1.64 ± 0.07	6.52	< 0.001
Body mass (kg)	69.6 ± 5.2	55.7 ± 6.7	6.70	< 0.001
Body fat (%)	12.6 ± 3.5	22.6 ± 3.9	7.99	< 0.001
Fat mass (kg)	8.7 ± 2.5	12.7 ± 3.2	4.06	< 0.001
Fat free mass (kg)	60.9 ± 5.5	43.0 ± 4.7	10.19	< 0.001
$\dot{V}O_{2\,max}$ ($l \cdot min^{-1}$)	5.09 ± 0.60	3.31 ± 0.41	10.08	< 0.001

Source: Appendix 7·2

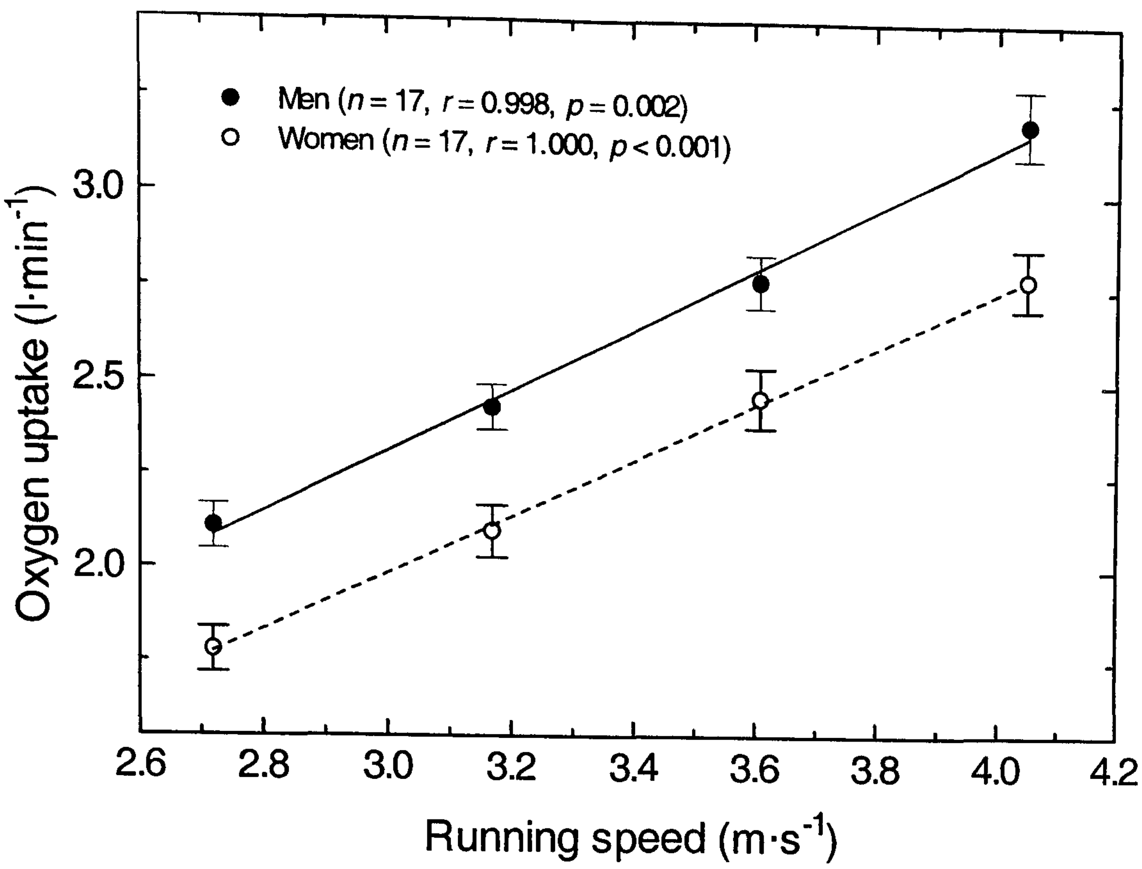

Figure 7·1: Oxygen uptake at each running speed for the men (●) and women (○). Values are mean ± SEM .

As illustrated in Figure 7·1, the relationship between $\dot{V}O_2$ at the four running speeds is linear which is confirmed by correlation coefficients of 0.998 (p = 0.002) for the men and 1.000 (p < 0.001) for the women. This confirms that a common running speed parameter is appropriate in the models below.

A positive relationship between $\dot{V}O_2$ and body mass was identified (p < 0.01) with correlation coefficients of 0.627, 0.681, 0.675 and 0.521 for the men and 0.680, 0.820, 0.781 and 0.786 for the women, at the respective running speeds 2.72, 3.17, 3.61 and 4.05 $m{\cdot}s^{-1}$. This highlights the influence of body size at all running speeds and justifies the need to scale the data to account for this influence.

Table 7·2: Expression of oxygen uptake at four running speeds. Values are mean (SEM).

	2.72 $m \cdot s^{-1}$		3.17 $m \cdot s^{-1}$		3.61 $m \cdot s^{-1}$		4.05 $m \cdot s^{-1}$		Sex
	Male	Female	Male	Female	Male	Female	Male	Female	
	n = 17	n = 17	n = 17	n = 17	n = 17	n = 17	n = 17	n = 17	p
Absolute ($l \cdot min^{-1}$)	2.11 (0.06)	1.78 (0.06)	2.43 (0.06)	2.10 (0.07)	2.77 (0.07)	2.46 (0.08)	3.19 (0.09)	2.78 (0.08)	0.001
Ratio Standard ($ml \cdot BM^{-1} \cdot min^{-1}$)	30.4 (0.6)	32.1 (0.8)	35.0 (0.6)	37.8 (0.7)	39.8 (0.8)	44.2 (0.9)	46.0 (1.1)	50.0 (0.9)	0.005
BM allometric model ($ml \cdot BM^{-0.75} \cdot min^{-1}$)	88.3 (1.9)	88.0 (2.2)	101.6 (1.9)	103.7 (2.0)	115.6 (2.4)	121.2 (2.4)	133.5 (3.2)	137.3 (2.6)	0.209
FFM allometric model ($ml \cdot FFM^{-0.50} \cdot min^{-1}$)	273 (6)	274 (8)	315 (6)	323 (9)	358 (8)	377 (10)	413 (11)	427 (10)	0.097
FFM & fat mass allometric model ($ml \cdot FFM^{-0.63} \cdot exp(0.018 \cdot FM^*) \cdot min^{-1}$)	135 (3)	132 (3)	155 (3)	155 (3)	176 (4)	181 (4)	204 (5)	205 (4)	0.739

*FM - fat mass

Source: Appendix 7·3

Body mass ratio standard

1. Body mass ratio standards at the four running speeds were calculated and summary presented in Table 7·2; see Appendix 7·3 for individual data. There was evidence of a *sex* $\times$ *speed* interaction ($F = 6.0$, $p = 0.003$), and so the variable was retained in the model. As illustrated in Figure 7·2, this interaction was due to the women's values (ml·kg·min^{-1}) increasing at a faster rate than the men's and is especially apparent at the two fastest running speeds. Figure 7·2 also illustrates a clear gender difference with the women having a higher average $\dot{V}O_2$ at all running speeds. This apparent gender difference was confirmed by the repeated measures ANOVA ($F = 8.87$, $p = 0.005$). Correlating the body mass ratio standards with body mass at each running speed, coefficients of -0.105, -0.091, -0.005, -0.152 for the men and -0.184, -0.082, -0.203 and -0.246 for the women ($p > 0.25$) indicated that $\dot{V}O_2$ at all four running speeds had been successfully expressed free from the influence of body mass. However, it is worth noting that all coefficients were negative, indicating that, although not significant, some over-scaling might have occurred.

Body mass allometric models

2. After adjusting for the influence of the covariate *ln*BM, results from the repeated measures ANCOVA identified no gender difference in running economy ($F = 1.64$, $p = 0.209$), negating the need to check for a *sex* $\times$ *ln*BM or *sex* $\times$ *speed* interaction and these variables were removed from the model. There was no evidence of a *speed* $\times$ *ln*BM interaction ($F = 1.94$, $p = 0.128$) and the variable was also removed from the model. This confirms the commonality of the slope at each running speed and justifies the scaling of sub-maximal $\dot{V}O_2$ using a

common body mass scaling exponent. As expected, analysis identified a running speed effect ($F = 6.01$, $p < 0.001$) and estimated parameters (± SEE) of -2.68 (0.44), -2.42 (0.38), -1.91 (0.41) and -1.84 (0.43) for running speeds 2.72, 3.17, 3.61 and 4.05 $m \cdot s^{-1}$, respectively. The covariate *ln*BM was also significant ($F = 62.9$, $p < 0.001$) with parameters of 0.808 (0.106), 0.783 (0.092), 0.694 (0.099) and 0.709 (0.105) for the same running speeds. Variables $ln\,\dot{V}O_2$ and *ln*BM were exponentiated and the following allometric model for each running speed was derived:

$$\dot{V}O_{2\,,\,2.72\ m\cdot s^{-1}} = 0.0686 \cdot BM^{0.808}$$

$$\dot{V}O_{2\,,\,3.17\ m\cdot s^{-1}} = 0.0889 \cdot BM^{0783}$$

$$\dot{V}O_{2\,,\,3.61\ m\cdot s^{-1}} = 0.1481 \cdot BM^{0.694}$$

$$\dot{V}O_{2\,,\,4.05\ m\cdot s^{-1}} = 0.1588 \cdot BM^{0.709}$$

Power function values for $\dot{V}O_2$ were calculated ($ml \cdot BM^{-b} \cdot min^{-1}$) for each running speed and correlated with body mass. Coefficients of -0.012, -0.020, -0.003, 0.000 ($p > 0.90$) indicated that $\dot{V}O_2$ had been successfully expressed free from the influence of body mass. Using the guidelines given by Snedecor & Cochran (1984), a pooled body mass scaling exponent of 0.749 (0.049) was calculated. Using this pooled body mass exponent, $\dot{V}O_2$ values at all running speeds were calculated ($ml \cdot BM^{-0.749} \cdot min^{-1}$) and presented in Table 7·2; see Figure 7·3 for illustration and Appendix 7·3 for individual data. A pooled running speed parameter of 0.323 (0.015) and intercept of -3.31 (0.21) were also calculated and together with the pooled body mass scaling exponent were used to generate a generic running economy allometric model:

$$\dot{V}O_{2\,,\,speed} = BM^{0.749} \cdot \exp(-3.31 + 0.323 \cdot speed) \cdot \in$$

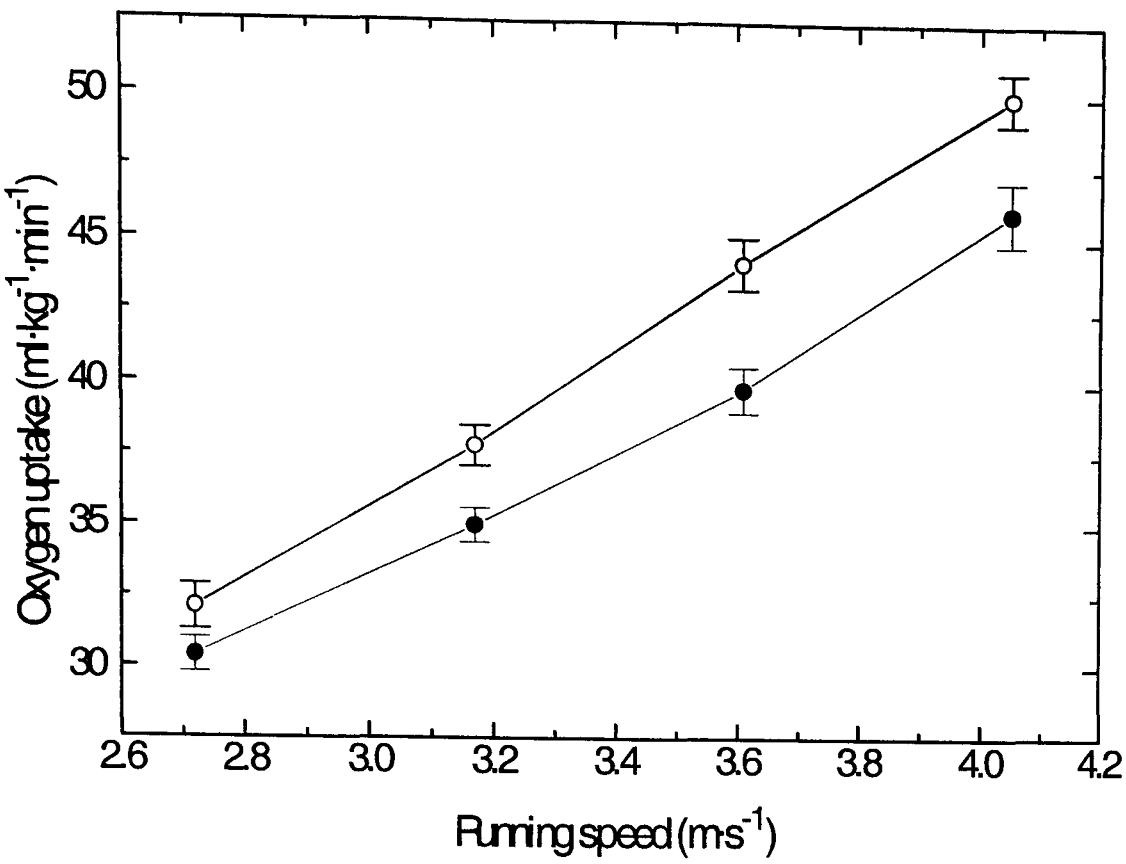

Figure 7·2: Oxygen uptake expressed as ratio standards at each running speed for the men (●) and women (○). Values are mean ± SEM.

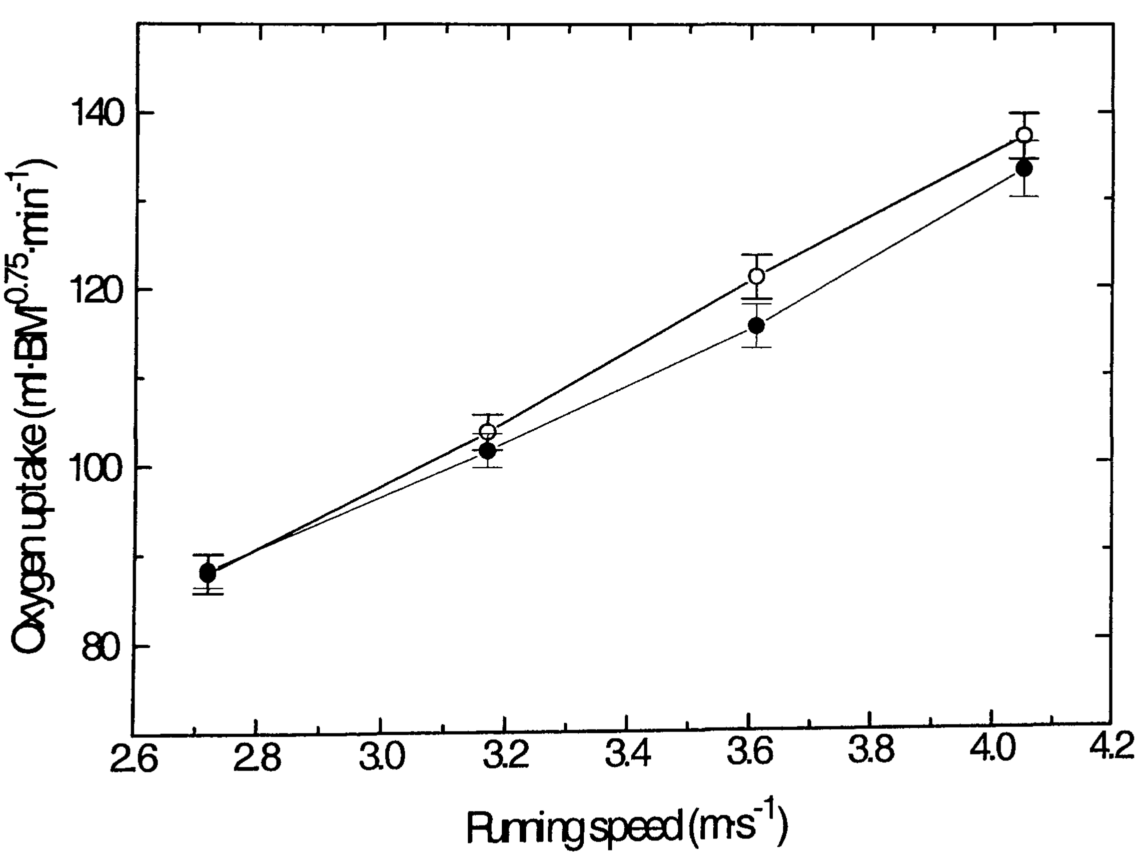

Figure 7·3: Oxygen uptake expressed as body mass power function ratios (ml·BM$^{-0.75}$.min^{-1}) each running speed for the men (●) and women (○). Values are mean ± SEM.

This model estimates $\dot{V}O_2$ at a selected running speed (2.72 - 4.05 $m \cdot s^{-1}$) given a participant's body mass, providing the participant is selected from a similar population of distance-runners.

3. The repeated measures ANCOVA on the body mass and fat allometric model identified the variable *fat* as not significant ($F = 1.97$, $p = 0.170$), rendering the model identical to that in **2**.

Fat free mass allometric models

2. After adjusting for the influence of *ln*FFM, no gender difference in running economy was identified ($F = 2.90$, $p = 0.098$), negating the need to check for a *sex* × *ln*FFM or *sex* × *speed* interaction and these variables were removed from the model. Further, there was no evidence of a *speed* × *ln*FFM interaction ($F = 2.23$, $p = 0.105$), confirming that a common slope on fat-free mass applies at each running speed, and the variable was also removed from the model. Repeated measures ANCOVA identified a running speed effect ($F = 10.4$, $p < 0.001$) and estimated parameters (± SEE) of -1.54 (0.36), -1.23 (0.33), -0.89 (0.35) and -0.74 (0.36) for respective running speeds 2.72, 3.17, 3.61 and 4.05 $m \cdot s^{-1}$. The covariate *ln*FFM was also significant ($F = 34.4$, $p < 0.001$) with parameters of 0.558 (0.090), 0.519 (0.084), 0.448 (0.088) and 0.465 (0.091) for the same running speeds. Power function values for $\dot{V}O_2$ were calculated ($ml \cdot FFM^{-b} \cdot min^{-1}$) for each running speed and correlated with fat-free mass. Coefficients of -0.022, -0.029, -0.015, 0.015 ($p > 0.85$) indicated that $\dot{V}O_2$ had been fully adjusted to be free from the influence of fat-free mass. A pooled fat-free mass scaling exponent of 0.497 (0.044) was calculated and used to calculate values for $\dot{V}O_2$ at all running speeds (ml·FFM$^{-0.497}$·min^{-1}); the summary values are presented in Table 7·3 (Appendix 7·3) and illustrated in Figure 7·3. A pooled running speed parameter of 0.323 (0.018) and intercept of -2.17 (0.18) were also calculated and together with the pooled fat-free mass exponent were used to generate the following running economy allometric model:

$$\dot{V}O_{2\,,\,speed} = \text{FFM}^{0.497} \cdot \exp(-2.17 + 0.323 \cdot speed) \cdot \in$$

3. After adjusting for the influence of covariates *ln*FFM and *fat*, no gender difference in running economy was identified ($F = 0.11, p = 0.739$), negating the need to check for a *sex* × *ln*FFM, *sex* × *speed* and *sex* × *fat* interactions and these variables were removed from the model. There was no evidence of a *speed* × *ln*FFM ($F = 1.27, p = 0.305$) or *speed* × *fat* ($F = 0.78, p = 0.517$), confirming the commonality of the fat-free mass slope and *fat* parameter at each running speed, and the variables were also removed from the model. Repeated measures ANCOVA identified a running speed effect ($F = 4.7$, $p < 0.01$) and estimated parameters (± SEE) of -2.13 (0.39), -1.98 (0.33), -1.58 (0.35) and -1.51 (0.37) for running speeds 2.72, 3.17, 3.61 and 4.05 m·s^{-1}, respectively. Covariates *ln*FFM ($F = 62.9, p < 0.001$) and *fat* ($F = 14.3, p < 0.001$) were also significant with parameters of 0.669 (0.092), 0.658 (0.078), 0.592 (0.082) and 0.608 (0.086) for *lnFFM* and 0.0147 (0.0054), 0.0184 (0.0046), 0.0190 (0.0048) and 0.0189 (0.051) for *fat*, for the respective running speeds 2.72, 3.17, 3.61 and 4.05 m·s^{-1}. Power function values for $\dot{V}O_2$ were calculated (ml·FFM^{-b}·exp(d·fat)·min^{-1}) for each running speed and correlated with fat-free mass, coefficients of 0.004, 0.013, 0.023, 0.015 (p > 0.90) indicated that $\dot{V}O_2$ had been successfully expressed free from the influence of fat-free mass. No relationship was found between the power function values and fat ($p > 0.90$). A pooled fat-free mass scaling exponent of 0.633 (0.041) and pooled fat parameter 0.0177 (0.0024) were calculated and used to construct values for $\dot{V}O_2$ at all running speeds ($ml \cdot FFM^{-0.633} \cdot exp(0.0177*fat) \cdot min^{-1}$), summary values are presented in Table 7·3 (Appendix 7·3) and illustrated in Figure 7·4. A pooled running speed parameter of 0.323 (0.015) and intercept of -2.89 (0.18) were also calculated and together with the pooled fat-free mass exponent and *fat* parameter were used to generate the following running economy allometric model:

$$\dot{V}O_{2\,,\,speed} = FFM^{0.633} \cdot \exp(-2.17 + 0.0177 \cdot fat + 0.323 \cdot speed) \cdot \in$$

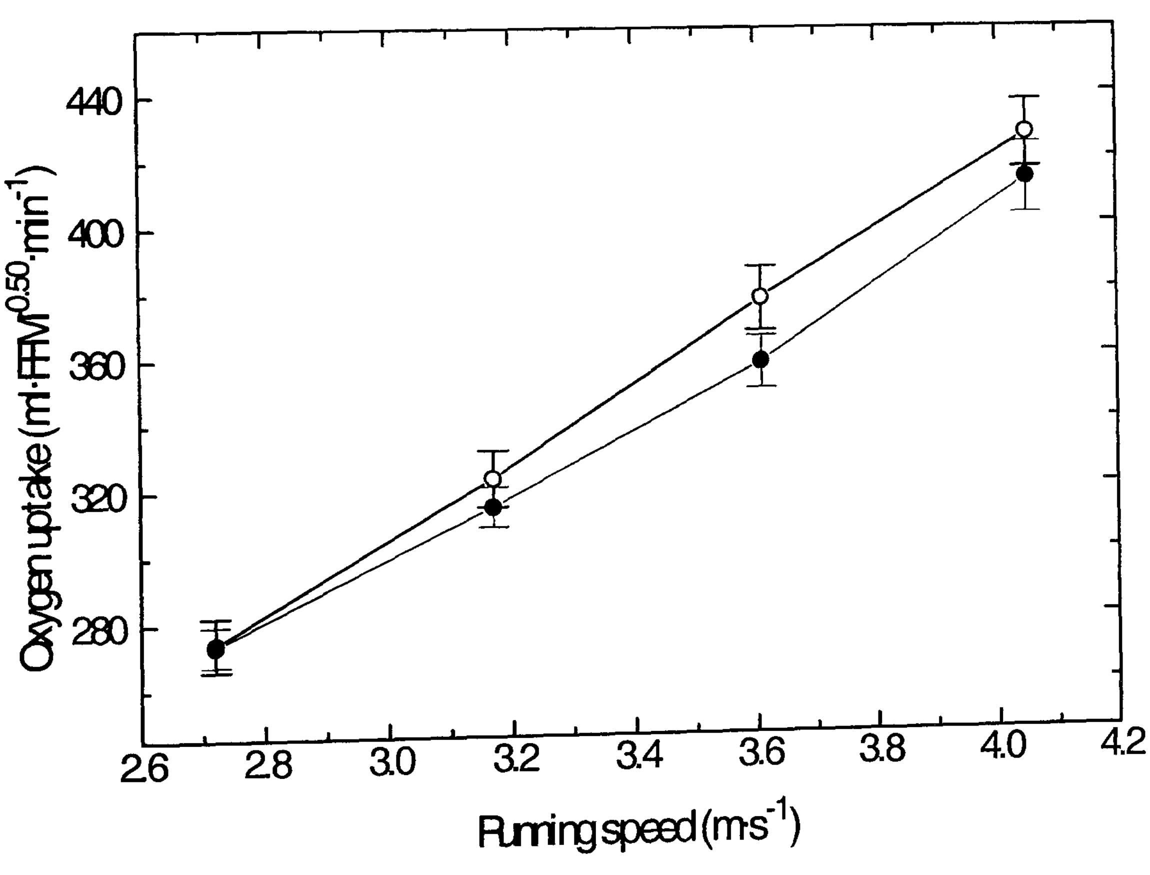

Figure 7·4: Oxygen uptake expressed as fat free mass power function ratios ($ml \cdot FFM^{-0.75}.min^{-1}$) at each running speed for the men (•) and women (○). Values are mean ± SEM.

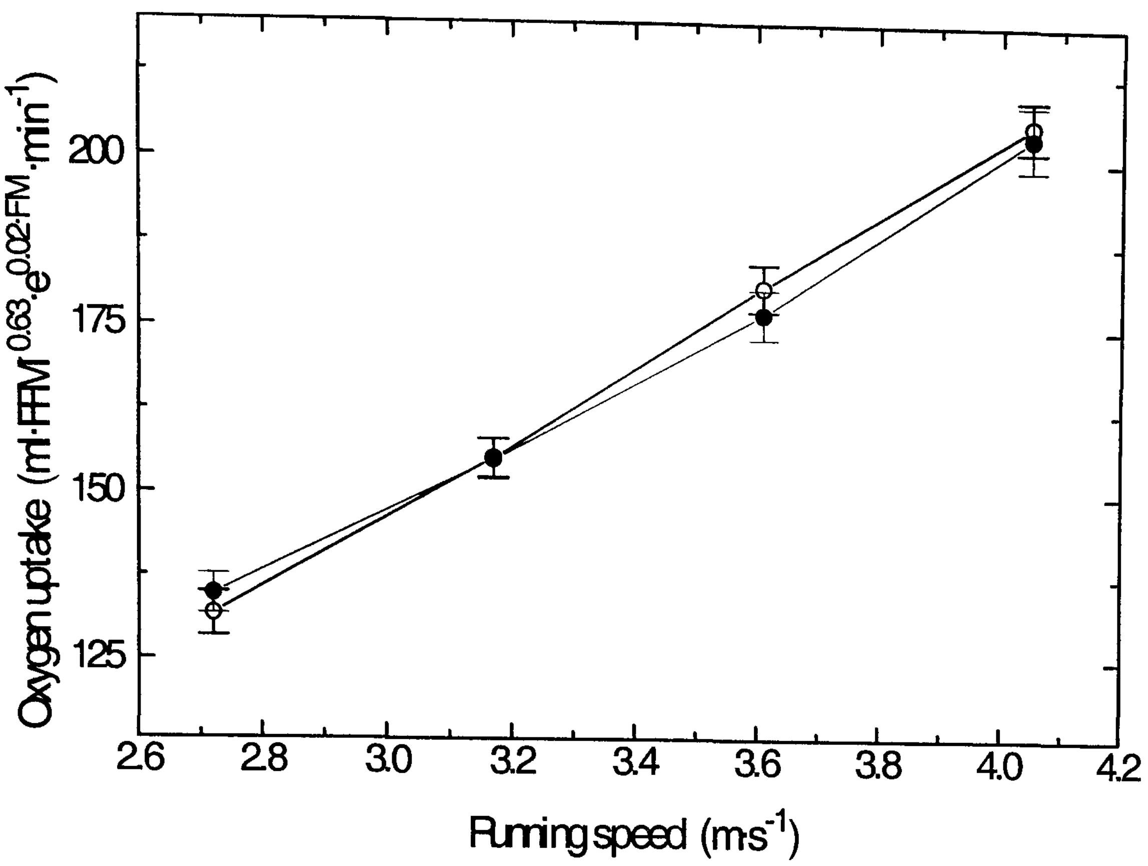

Figure 7·5: Oxygen uptake expressed as fat free mass & fat power function ratios (ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1}) at each running speed for the men (●) and women (○). Values are mean ± SEM.

Regression diagnostics

In all models no relationship ($p > 0.20$) was found between the absolute residuals and predictor variables and the residuals from all models were normally distributed ($p > 0.20$). In the fat-free mass and fat mass allometric model the tolerance and VIF values (0.800 & 1.25, respectively) differed only slightly from unity, indicating little influence of collinearity between *ln*FFM and fat mass.

DISCUSSION

The basis for this study is that an athlete's sub-maximal $\dot{V}O_2$, at all running speeds is influenced by their body size. This influence was identified at all four running speeds ($p < 0.01$) and justifies the need to scale the values for $\dot{V}O_2$ accordingly. However, the apparent running economy of the male and female middle- and long-distance runners was influenced by the scaling technique used.

Analysis using the body mass ratio standards identified the women to have a higher $\dot{V}O_2$ (ml·BM^{-1}·min^{-1}) at all four running speeds than the men ($p = 0.005$), inferring that the men had a better running economy. The analysis also revealed a *sex* $\times$ *speed* interaction, which was due to the women's values apparently increasing at a faster rate than the men's. This interaction implies that there are systematic differences in the running economy between men and women. Results from the bivariate correlation of the ratio standards with body mass would seem to suggest that $\dot{V}O_2$ values were independent of body mass and had been correctly scaled. Although, all coefficients were negative, indicating that some 'over-scaling' had occurred, but as none of these coefficients were significant any distortion was supposedly acceptable. Furthermore, results from the regression analysis indicated that the residuals were normally distributed and heterogeneous thus confirming that the findings from this scaling model should be accepted.

In contrast to the body mass ratio standards, the body mass allometric model found no gender difference in running economy ($p = 0.209$). The expressed $\dot{V}O_2$ values (ml·BM^{-b}·min^{-1}) were rendered independent of body mass and residuals from the ANCOVA were found to be acceptable, thus again confirming the appropriateness of the model and supporting the findings. Similar findings were also made with the fat-free mass allometric model. No gender difference in running economy was identified (p = 0.097) and model diagnostics confirmed the appropriateness of the model. However, the addition of fat mass added significant information to the fat-free mass allometric model and further improved the sensitivity of the *ln*FFM variable (F value increased from 34.4 to 62.9).

The ratio standard and allometric models satisfy the statistical assumptions that underpin a parametric test but give different outcomes. There either is, or is not a gender difference in running economy and either the ratio standard or allometric models (BM & FFM) are correct with the other distorting values for $\dot{V}O_2$ and confounding interpretation. The nature of the ANCOVA on the log-transformed data used in the body mass allometric model implies the sample-specific relationship between $\dot{V}O_2$ and body mass. The parameter for *ln*BM identified at each running speed ranged from 0.694 to 0.808, with only the 95 % confidence interval of the largest parameter (0.808) just encompassing unity (0.600, 1.016). This would suggest that the relationship between sub-maximal $\dot{V}O_2$ and body mass in this sample is less than unity and that the ratio standard has distorted the values for $\dot{V}O_2$ by 'over-scaling'.

In juxtaposition to the effect on $\dot{V}O_{2\,max}$ identified in study **2**, this 'over-scaling' will tend to disadvantage the smaller and lighter athletes (i.e. women) by artificially inflating their scaled values for $\dot{V}O_2$ at all running speeds and thus reduce their estimated running economy. This 'over-scaling' further confounds interpretation by doing the opposite to the scaled values of $\dot{V}O_2$ for the larger and heavier participants (i.e. men). What is troubling is that the bivariate correlations failed to identify a significant relationship between the ratio standard and body mass indicating that values were expressed independent of body size. One indication of possible distortion was that all coefficients were negative, suggesting possible 'over-scaling'.

Assuming the appropriateness of the allometric models, an example of how the 'over-scaling' of the ratio standards can lead to misinterpretation is provided in Table 7·3. The example is made using estimated values for $\dot{V}O_2$ ($l \cdot min^{-1}$) at 4.44 $m \cdot s^{-1}$ (16 $km \cdot hour^{-1}$) using the body mass allometric model for athletes with body mass of 55, 70 and 85 kg. Although outside the range used in this study, the speed was selected to make comparison with the running economy standards set by Jones (2000) using the ratio standard. As can be seen from the table, the $\dot{V}O_2$ values expressed using the body mass allometric model ($ml \cdot kg^{-0.749} \cdot min^{-1}$) are identical, which is to be expected using the same model to estimate the absolute values for $\dot{V}O_2$. However, using the ratio standard the apparent running economy of these three athletes now differs. The largest athlete, weighing 85 kg, now appears to have the best running economy and the lightest athlete, weighing 55 kg, the poorest. Comparing these values with the standard of 52 $ml \cdot kg^{-1} \cdot min^{-1}$ recommended by Jones (2000) would place the lightest athletes as having poor running economy and would erroneously warrant changes to their training program. This distortion arises as the ratio standard over-estimates the influence of body size. This clearly demonstrates how an inappropriate standard causes misinterpretation.

Table 7·3: Estimated oxygen uptake at 4.44 $m \cdot s^{-1}$ using the body mass allometric model and comparison with the ratio standard.

	Oxygen uptake		
Body mass	$(l \cdot min^{-1})$	$(ml \cdot kg^{-1} \cdot min^{-1})$	$(ml \cdot kg^{-0.749} \cdot min^{-1})$
55 kg	3.09	56.1	154
70 kg	3.70	52.8	154
85 kg	4.28	50.3	154

Of the allometric models, the two to consider for expression of running economy are the body mass and fat-free mass & fat mass models. The simplest of the two is the body mass allometric model in which comparison is easily made just by knowing the athlete's body mass and running speed at which $\dot{V}O_2$ is collected. This has physiological justification, as apart from the energy required to maintain basal metabolic function the additional oxygen required is due to the speed of locomotion and the total load that is being moved. However, in comparisons of athletes with substantially different body compositions, such as between men and women, or in longitudinal studies, where an athlete's body composition and/or size is likely to change over time, the extra sensitivity attained by breaking body mass into its fat-free mass and fat mass constituents should be preferred.

Chapter 8

DISCUSSION

The purpose of these studies was to investigate maximal and sub-maximal oxygen uptake of men and women and, using appropriate scaling methodology, partition out the influence of body size and make meaningful comparison between the genders. It was hypothesised that traditional scaling methods, based on the ratio standard, fail to remove the influence of body size and lead to distortions of the data. These distortions increase the possibility of misinterpretation. Moreover, the use of non-linear allometric modelling would be demonstrated to be a superior scaling technique as it renders values for maximal and sub-maximal $\dot{V}O_2$ independent of size and models the multiplicative error structure often associated with physiological data of this type more appropriately.

Summary from individual studies

Study **1** Modelling maximal oxygen uptake in male and female distance runners.

The body mass ratio standards were found to be successful in rendering $\dot{V}O_{2\,max}$ values independent of body size but residual error was found to be heteroscedastic and unsuitable for analysis. The fat free mass ratio standards were also found to render $\dot{V}O_{2\,max}$ independent of size but the residual error was normal indicating that the data had been appropriately scaled. Both power function ratio models (ml·BM$^{-0.67}$·min^{-1} & ml·BM$^{-0.75}$·min^{-1}) were inappropriate as they 'under-scaled' the data and lead to distortion. Both allometric models (BM & FFM) successfully scaled values for $\dot{V}O_{2\,max}$ and identified body size exponents (± SEE) of 0.94 (0.10) and 0.98 (0.12), for body mass and fat free mass, respectively. Fat free mass was chosen in preference to body mass as it better reflected the aerobic qualitative characteristics of the tissues in men and women and, as such, is a more valid measure. The fat free mass ratio standard was the simplest and most appropriate model and estimated this gender difference at 9 %. With a small sample size and body size range, caution was urged in interpretation.

Study **2** Modelling maximal oxygen uptake in male and female International-standard endurance athletes.

The body mass and fat free mass ratio standards were inappropriate and 'over-scaled' values for $\dot{V}O_{2\,max}$. This 'over-scaling' distorted the data and led to misinterpretation. Power function ratios (ml·BM$^{-0.67}$·min^{-1}) correctly scaled the values for $\dot{V}O_{2\,max}$ in the women but not in the men, rendering the gender by sport comparison meaningless. Both allometric models successfully scaled $\dot{V}O_{2\,max}$ and were further improved by the addition of age (*age* & *age*^{2}). The fat free mass allometric model was chosen in preference to the body mass model as it better reflected the research question. No difference was found between the four categories of sport and $\dot{V}O_{2\,max}$ in the men was 15 % higher than the women.

Study **3** Modelling the influence of age, physical activity, body size and gender on maximal oxygen uptake in older humans.

The study identified a decline in $\dot{V}O_{2\,max}$ with increasing age commensurate with a decline in body mass and fat free mass in older men but not in older women. Both allometric models successfully scaled $\dot{V}O_{2\,max}$ and age and were further improved by the addition of physical activity. As per study **2**, the extra sensitivity gained by accounting for differences in body composition meant that the fat free mass allometric model should be used in preference to the body mass model. Using this model, no gender difference in $\dot{V}O_{2\,max}$ was found and an age-associated decline in $\dot{V}O_{2\,max}$ of 1.5 % per annum was estimated.

Study **4** Modelling sub-maximal oxygen uptake in male and female distance runners.

The body mass ratio standards were found to be inappropriate and had artificially created a gender difference in running economy, making the women appear less economical than the men. All allometric models correctly scaled sub-maximal $\dot{V}O_2$ and found no gender difference in running economy. Dependent on the research question being investigated, the two models of choice were the body mass and fat free mass & fat allometric models. For simplicity, the body mass allometric model was recommended but in comparisons where there are large group differences in body composition or measurements are made over time, the fat free mass & fat allometric model should be used. One problem highlighted was the failure of the bivariate correlation (BM ratio standards & BM) to detect the distortion and misinterpretation of running economy caused by using the body mass ratio standard.

Summary of modelling $\dot{V}O_{2max}$

The results from these studies imply that, in general, the use of a ratio per-body size standard (ml·kg^{-1}·min^{-1}) is an inappropriate scaling method. In most cases, these ratio standards 'over-scaled' the data and led to distortion and misinterpretation. This 'over-scaling' was due to an over-estimation of the influence of body size on $\dot{V}O_{2\,max}$. The ratio standard assumes a linear relationship between body size and $\dot{V}O_{2\,max}$, denoted by a body size exponent of unity, and implies that a doubling of body size results in a doubling of $\dot{V}O_{2\,max}$.

Table 8·1 Pooled body size exponents (95 % C.I.) from all studies.

			Pooled exponent (b)	
Study	Measure	N	Body mass	Fat free mass
1	$\dot{V}O_{2\,max}$	♀ = 17 ♂ = 17	0.94 (0.71, 1.17)	0.98 (0.77, 1.18)
2	$\dot{V}O_{2\,max}$	♀ = 69 ♂ = 50	0.68 (0.61, 0.75)	0.80 (0.72, 0.88)
3	$\dot{V}O_{2\,max}$	♀ = 146 ♂ = 152	0.58 (0.44, 0.72)	0.96 (0.86, 1.05)
4	Sub-max $\dot{V}O_2$	♀ = 17 ♂ = 17	0.75 (0.65, 0.85)	0.63 (0.55, 0.71)

However, as illustrated in Table 8·1, the estimated relationship between body size and $\dot{V}O_{2\,max}$ (studies **1** – **3**) in various populations appears to be curvilinear, in the majority of cases, and in all cases identified a body size exponent of less than unity. Thus, the ratio standards over-accounted for the influence of body size and 'over-scaled' values for $\dot{V}O_{2\,max}$. This 'over-scaling' will tend to advantage the smaller and lighter participants by artificially inflating their scaled values for $\dot{V}O_{2\,max}$. 'Over-scaling' further confounds by doing the opposite to the scaled values for $\dot{V}O_{2\,max}$ for the larger and heavier participants. Owing to the difference in body size between men and women this distortion, at best, just clouded interpretation and decreased the apparent gender difference in $\dot{V}O_{2\,max}$. In study **2** however, where there were also large within-gender body size differences between the four sports (long- & middle-distance runners and light- & heavyweight rowers), the 'over-scaling' due to the inappropriate use of the ratio standard artificially created a significant difference between sports.

Table 8·2 Gender difference in $\dot{V}O_{2\,max}$. Values are percentages (95 % C.I.).

			Gender difference (%)	
Study	Measure	*N*	Body mass	Fat free mass
1	$\dot{V}O_{2\,max}$	♀ = 17 ♂ = 17	24.5 (16.2, 33.3)	9.6 (1.0, 19.0)
2	$\dot{V}O_{2\,max}$	♀ = 69 ♂ = 50	29.4 (25.9, 33.0)	15.3 (11.5, 19.2)
3	$\dot{V}O_{2\,max}$	♀ = 146 ♂ = 152	28.4 (22.2, 34.9)	No difference

It was evident from studies **1** and **2** that the use of power function ratios ($ml \cdot kg^{-b} \cdot min^{-1}$), constructed using theoretical values of either 0.67 or 0.75 as the body size exponent, were also inappropriate. In all but one case (study **2** for the women), these power function ratios where found to under-estimate the influence of body size and, in contrast to the ratio standards, 'under-scaled' values for $\dot{V}O_{2\,max}$.

In all cases, non-linear allometric modelling was found to be appropriate for scaling values of $\dot{V}O_{2\,max}$. Even in the single case in which a fat free mass ratio standard was found to be suitable (study **1**), the allometric model was a viable alternative. This demonstrates the versatility of allometric modelling. When a linear model is appropriate this will be identified by a body size exponent of near unity. However, a caveat to this is the further identification of the correct error structure (addictive not multiplicative), which of course should always be verified.

It is only after appropriate scaling that values of $\dot{V}O_{2\,max}$ are expressed free from the influence of body size and meaningful gender comparisons can be made. However, as demonstrated in studies **2** and **3**, this can only be achieved by considering other influences, such as age, physical activity and sport, and, where appropriate, correctly incorporating them into the allometric model as covariates.

Gender difference in $\dot{V}O_{2\,max}$ from the three studies are summarised in Table 8·2. Owing to the influence of the sex-specific differences in body composition the apparent gender difference depends on the choice of body size variable, body mass or fat free mass.

Using body mass as the body size variable, the estimated gender difference from the three studies are surprisingly similar (24.5 - 29.4 %), even though they are derived from different populations. However, all estimates compare well with values published by Rogers *et al.* (1995) and Heil (1997) who both used allometric modelling to scale $\dot{V}O_{2\max}$. Further to confirming the suitability of using a power function ratio (ml·kg$^{-0.75}$·min^{-1}) to scale $\dot{V}O_{2\max}$ in adult men and women, Rogers *et al.* (1995) reported a gender difference of 28.9 %. Similarly, Heil (1997) estimated a gender difference of 25.6 % in a 'healthy' population of 230 women and 210 men, after first identifying a common body mass exponent of 0.76. This implies that whether the sample is from a normal and/or older population or from a group of elite endurance athletes the gender difference in $\dot{V}O_{2\max}$ appears to be the same, equal to approximately 27 %.

Although traditionally body mass is the body size variable of choice, its indiscriminate use has been criticised (Batterham *et al.*, 1999; Vanderburgh & Katch, 1996). Their argument is that body mass includes a component of fat mass, which is virtually inert and uses little O_2, and '...could spuriously affect the magnitude of the exponent obtained empirically' (Vanderburgh & Katch, 1996, *p.* 1204). Moreover, because women have a greater proportion of body fat, the use of body mass does not account for gender differences in body composition. Thus, in comparison of the aerobic quality of the tissues, the apparent gender difference will be confounded and over-estimated. For example, given a 70 kg man and woman with an average body fat of 15 % and 27 %, respectively (McArdle *et al.*, 1991), the man has over 16 % more oxygen using lean tissue than the woman. Clearly, this extra lean tissue will always disadvantage the women when comparison is made using body mass as the body size variable.

Fat free mass represents the component of body mass that is devoid of fat mass and as such should be more valid and sensitive as the body size variable because it should account for within- and between-gender differences in body composition. Accordingly, comparisons of aerobic tissues of the men with those of the women should be improved. Use of fat free mass as the body size variable in study **3** revealed no gender difference, indicating that the aerobic quality of the tissues is the same in older men and women. In younger and fitter populations (Studies **1** & **2**) a gender difference in $\dot{V}O_{2\,max}$ was still apparent, but smaller, with men having a higher value than women (9.6 % & 15.3 %, respectively). Döbeln (1956) investigated the relationship between $\dot{V}O_{2\,max}$ and fat free mass in men and women and identified a common fat free mass scaling exponent of 0.71. Although, as both the men and women were combined into one group, no gender comparison was made. No other study has been published which used allometric modelling to compare $\dot{V}O_{2\,max}$ between men and women using fat free mass as the body size variable.

Owing to sex-specific hormones, such as testosterone and growth hormone, men tend to have a higher proportion of muscle mass than women (Nicklaus *et al.*, 1995), which is the primary user of O_2 during exercise. Although the use of fat free mass attempts to account for differences in body fat it might not be sensitive to this gender difference in lean muscle mass proportion. Lean muscle mass accounts for approximately 53 % of fat free mass in the average man whilst only 49 % in the average women (Behnke, 1969), a confounding difference of approximately 7 %. If this gender difference in lean muscle mass proportion is maintained in the samples from studies **1** & **2** then this could account, in part, for the small gender difference in $\dot{V}O_{2\,max}$ identified (9.6 % & 15.3 %, respectively). For example, after adjusting the data in studies **1** & **2** to account for this theoretical 7 % difference in muscle mass proportions, the estimated gender difference in VO_{2max} in study **2** dropped from 15.3 % to 9.0 % and was no longer significant in study **1** (p = 0.596). Moreover, Shepherd, Bouhlel, Vandewalle and Monod (1988) found no gender difference in $\dot{V}O_{2\,peak}$ during arms or legs only exercise when comparison was made after adjusting for difference in muscle mass. However, comparison was made using the ratio standard and, as such, the results should be treated with caution.

The fact that no gender difference in $\dot{V}O_{2\,max}$ was identified in the older population of study **3** lends further credence to idea that gender differences in $\dot{V}O_{2\,max}$ in younger participants (studies **1** & **2**) could be due, in part, to differences in lean muscle mass proportions. As discussed in study **3**, both human growth hormone secretion (Isaksson *et al.*, 1985) and testosterone concentrations decline with advancing age (Gray *et al.*, 1991; Proctor *et al.*, 1998). This decline has been shown to be mirrored by a loss of lean body mass (Larsson & Karlsson 1978; Balagopal *et al.*, 1997) which is ultimately due to a loss of muscle mass. In addition, this decline affects predominantly the men as older women do not experience such a change in growth hormone and testosterone with advancing age (Isaksson *et al.*, 1985). Thus, in older men and women the gender difference in muscle mass proportion might no longer exist and would therefore not confound interpretation.

Ideally to ensure that gender comparison, is equitable future investigation should attempt to measure and use muscle mass as the body size variable. Several methods of determining this measure include the use of creatine content, potassium concentration and electrical conductivity (Heymsfield, Gallagher, Visser, Nunez & Wang, 1995). However, these measures are plagued by lack of reliability, depend on assumptions that are difficult to validate and are based on data derived from cadaver studies (Clarys, Martin & Drinkwater, 1984; Heymsfield *et al.*, 1995). As discussed by Mitsiopoulos, Baumgartner, Heymsfield, Lyons, Gallagher and Ross (1998), recent improvements in imaging technology, such as computerised tomography and magnetic resonance imaging, have allowed direct visualisation of images depicting skeletal muscle cross-sectional area. Such images in series, together with mathematical reconstruction algorithms, can produce accurate estimates of the mass of individual muscle groups or total skeletal muscle mass (Heymsfield *et al.*, 1995). Such technology is relatively new and expensive but should allow unbiased estimation of the oxygen using tissue during exercise and so detect whether a gender difference in $\dot{V}O_{2\,max}$ really does exist.

All three studies made original contribution to knowledge in meaningful comparison of $\dot{V}O_{2\,max}$ between men and women. Study **1** was the first to compare men and women (distance runners) using ratio standards, power function ratios and non-linear allometric modelling with body mass and fat free mass as the body size variable. Study **2** was the first to compare International standard male and female athletes from different endurance sports using non-linear allometric modelling and was even successful in identifying and accounting for the confounding influence of age. Moreover, to this author's knowledge, the study also reported the highest absolute value for $\dot{V}O_{2\,max}$ ($l \cdot min^{-1}$) ever reported. Applying similar methodology to study **3**, this was the first to report age-associated decline in $\dot{V}O_{2\,max}$ in older men and women with appropriate modelling. Furthermore, through physiological and statistical justification an allometric model was developed that incorporated the confounding influence of physical activity. Overall, all three studies laid the foundation for meaningful gender comparison of $\dot{V}O_{2\,max}$ and could be the basis for others who want to make similar comparisons.

Summary of sub-maximal $\dot{V}O_2$

As found with $\dot{V}O_{2\,max}$, the use of the ratio standard 'over-scaled' values for sub-maximal $\dot{V}O_2$ and this subsequent distortion of the data artificially created a gender difference in running economy. Allometric modelling was shown to be a superior alternative and when values for sub-maximal $\dot{V}O_2$ were correctly scaled no gender difference in running economy was found. This is similar to the findings in study **2**, and clearly demonstrates the importance of correct identification of the influence of size and the use of an appropriate scaling methodology to account for such influence. If the incorrect scaling methodology can sometimes lead to spurious differences being detected, then it is of little wonder that there is conflict in the published literature as to the gender difference in running economy. Of the few published studies that have investigated running economy using power function ratios ($ml \cdot kg^{-b} \cdot min^{-1}$) or, in one instance, allometric modelling, no gender difference was found. Davies *et al.* (1997) investigated the use of allometric modelling to account for differences in body size when comparing running economy in 12 male and 12 female distance runners. They identified a pooled body mass exponent of 1.01 in their sample, which justified the use of a ratio standard to make gender comparison. Similarly, after following an appropriate scaling methodology no gender difference in running economy was found. Both Helgerud (1994) and Rogers *et al.* (1995) used power function ratios ($ml \cdot kg^{-0.75} \cdot min^{-1}$) to make comparison and also found no gender difference in running economy.

The elements in this study made an original contribution to the knowledge on how to meaningful compare sub-maximal $\dot{V}O_2$ (running economy) between men and women. The study reported by Davies *et al.* (1997) was similar as they used allometric modelling to compare running economy in male and female runners.

Table 8·3: Summary of published exponents from allometric studies investigating VO_{2max}.

Study	Population	Sample	Body size exponent		
			Variable	*b*	SEE
VO_{2max}:					
Vanderburgh & Katch (1996)	Normal adult population	♀ = 94	FFM	1.04	0.26
Davies *et al*. (1995)	Normal older population	♂ = 73	BM	1.05	NP
Sjodin & Svednhag (1994)	Distance runners - children	♂ = 8	BM	1.01	0.04
	Untrained - children	♂ = 4	BM	0.78	0.07
Heil (1997)	Normal adult population	♀ = 230, ♂ = 210	BM	0.76	0.05
Welsman *et al*. (1996)	Normal adult & children population	♀ = 83, ♂ = 73	BM	0.80	0.04
Bergh *et al*. (1991)	Sub-elite endurance athletes	♀ = 57, ♂ = 84	BM	0.71	0.05
Rogers *et al.* (1995)	Normal adult & children population	♀ = 45, ♂ = 45	BM	0.92	NP
Nevill *et al*. (1992)	Recreationally active aldult	♀ = 129, ♂ = 179	BM	0.67	NP
Nevill *et al*. (1994)	Normal adult population	♀ = 880, ♂ = 852	BM	0.66	NP
Rosen *et al*. (1998)	Normal older population	♂ = 276	FFM	0.83	0.08
Kinch *et al*. (1993)	Elite rowers	♂ = 8	BM	0.88	NP
		♂ = 8	BM	0.99	NP
Sub-maximal VO_2:					
Davies *et al*. (1997)	Sub-elite distance runners	♀ = 12, ♂ = 12	BM	1.01	0.22

NP - not presented

However, they only assessed running economy at one running speed (3.58 m·s^{-1}) and did not investigate the possible influence of between and within-gender differences in body fat. This was the first time that men and women had been correctly compared using non-linear allometric modelling over four running speeds and incorporating the confounding influence of body composition. Procedures used should enable others to generate standards by which specific populations, such as endurance runners, can now be meaningfully compared.

Relationship of body size with $\dot{V}O_2$

As summarised in Table 8·1, pooled exponents from the four studies estimating the nature of the relationship between body size and maximal and sub-maximal $\dot{V}O_2$ show a wide variation (range: 0.58 - 0.98). The 95 % confidence intervals of some values comfortably encompass the theoretical values for the surface law (0.67) and/or McMahon law of elasticity (0.75), whereas others are much higher with their 95 % confidence intervals not encompassing either theoretical value but encompassing unity, indicating that linearity between changes in body size with $\dot{V}O_2$ may exist.

Higher than expected body size scaling exponents have plagued the literature for allometric modelling in human physiology (Batterham *et al.*, 1999; Nevill, 1994) and biological sciences (Weibel, 2002; Whitfield, 2001). For illustration, see Table 8·3, which gives a general overview of some of the published body size (BM & FFM) exponents from the exercise sciences. These higher than expected body size exponents have given greater credence to the value of 0.75 based on McMahon's (1973) theory of elasticity, especially in the fields of biology and ecology, and have led to much investigation into this apparent theoretical attenuation. Based on the findings of Alexander *et al.* (1981), that within species, larger mammals have a greater proportion of proximal leg muscle mass, Nevill (1994) introduced into the allometric model a further body size variable, stature. The introduction of stature as an additional covariate had the effect of reducing the original body mass exponent from 0.81 to 0.67, exactly as predicted from the 'surface-law'. However, this approach was criticised by Batterham *et al.* (1997) who argued that the strong correlation between body mass and stature caused collinearity problems and that '...restoration of the mean mass exponent to the anticipated 2/3 may be a fortuitous statistical artefact' (*p*. 693). This disagreement has generated a lot of lively debate but what remains is that in the empirical determination of the relationship between body size and $\dot{V}O_2$ much variation has been reported and no one single body mass exponent appears to exist.

As discussed earlier, geometric similarity lends itself to the 'surface-law' because of the following assumption:

$$\text{Body mass}^{1} \quad \infty \quad \text{Surface area}^{3/2} \quad \infty \quad \text{Stature}^{3} \qquad [1]$$

Rearranging this expression, concentrating on the proportionality between body mass and surface area, gives the 'surface-law':

$$\text{Body mass}^{2/3} \quad \infty \quad \text{Surface area}^{1} \qquad [2]$$

Such proportionality is easy to validate in simple structures, such as a cube or sphere (see page 20), but in more complicated systems, such as the human body, this proportionality might not apply. For example, body mass should be proportional to stature cubed. However, the body mass index, a stature-adjusted weight index used to identify overweight and/or obese individuals, is calculated by dividing body mass (kg) by stature (m) squared ($kg{\cdot}m^{-2}$). If dimensionality holds true for the human body then this index should be calculated using stature cubed. The body mass index has been validated many times (Cole, 1991) and in a recent review Nevill and Holder (1995b) reported that in the majority of their sample from the Allied Dunbar fitness survey (n = 2366) body mass was in fact proportional to stature squared. Incidentally, the exception to this was female subjects aged over 55 years where the exponent needed to render body mass independent of stature was even less than two.

If the theoretical proportionality between body mass and stature does not hold true, then it is unlikely that theoretical proportionality exists between body mass and surface area. Accepting the data used to create and validate the body mass index and from Nevill and Holder (1995b), this will have an impact on the proportionality between body mass and surface area:

$$\text{Body mass}^{1} \quad \infty \quad \text{Surface area}^{?} \quad \infty \quad \text{Stature}^{2} \qquad [3]$$

With a lower empirical proportionality exponent for stature it seems logical that the exponent for surface-area would also be lower. Assuming that the surface-area proportionality exponent drops by the same degree as the exponent for stature (50 % of the difference between body mass and stature), the new proportionality exponent for surface-area would be 5/4. Introducing this into [**3**] and rearranging to express BM^{b} proportional to surface-area would produce the following expression:

$$\text{Body mass}^{4/5} \quad \infty \quad \text{Surface area}^{1} \qquad [4]$$

Thus, if stature squared is proportion to body mass, the new theoretical 'surface-law' for human beings would be body mass raised to the power 0.80.

Exploring the data on the male and female International standard endurance athletes in study **2**, the relationship between the natural logarithm of body mass (lnBM) and stature (lnstature) was 3.09 (± 0.17). This value is close to the theoretical value of 3.0 expected from the 'surface-law' and confers with the pooled body mass exponent identified in the study of 0.68 (See Table 8·1). However, the influence of both sex ($t = 2.17, p = 0.032$) and sport ($t = 3.72, p < 0.001$) were significant. This sex difference implies that for a given stature these women would, on average, be heavier than the men. The sport difference relates to the demands of the individual sport; for a given stature the heavyweight rowers were, on average, heavier than the runners and the lightweight rowers. This is to be expected as heavyweight rowing is a weight-supported sport and it is advantageous for these athletes to be large (Shephard, 1998; Hagerman, 1972). Owing to body mass restrictions for competing (< 72 kg and < 59 kg for the men & women, respectively), lightweight rowers preclude these large individuals and the best performers tend to be tall and possess a more ectomorphic and endomorphic somatotype (Hagerman, 1984). Distance running is weight bearing and also tends to favour athletes that are predominantly ectomorphic in somatotype (Housch, 1988). Repeating the analysis but replacing *ln*BM with *ln*FFM, the relationship between *ln*stature dropped to 2.74 (SEE ± 0.14), which would be in keeping with the identification in the study of a higher pooled body size exponent of 0.80. The analysis still identified a sex ($t = 6.69, p < 0.001$) and sport ($t = 2.78, p = 0.006$) difference. However, the sex difference had now reversed, implying that for a given stature men have, on average, a greater fat free mass than women.

Exploring the data on the older men and women in study **3**, the relationship between *ln*BM and *ln*stature was 1.59 (SEE ± 0.15, $p < 0.001$), which is much lower than the value identified for International endurance athletes. The value is now closer to 2.0 used in the construction of the validated body mass index and identified in a more normal population by Nevill and Holder (1995).

These two contrasting examples illustrate how the relationship between body mass (& FFM) and stature differs between populations. If the proportionality between body mass and stature is variable, then so must the proportionality between body mass and surface-area. So, even if maximal and sub-maximal $\dot{V}O_2$ are truly related to surface-area, such variability in dimensionality could explain, in part, the wide-ranging values that have been reported in the literature for the body size scaling exponent.

Another theory that may, in part, explain the wide range of values reported for the body size scaling exponent of sub-maximal and maximal $\dot{V}O_2$ is that of Darveau *et al.* (2002). As discussed in chapter 2, they propose an 'allometric cascade' model in which the scaling exponent relating $\dot{V}O_2$ to body size is the sum of all influences governing metabolism. During exercise, O_2 supply is greatly increased to the muscles and this increase in the O_2 'delivery step' accounts for the higher than expected global scaling exponents reported.

Regardless of whether this theory is appropriate or due, in part, to differences in proportions between body mass and stature, there appears to be no one universal scaling exponent relating body size to $\dot{V}O_2$. So universal standards enabling comparison of a participant's oxygen handling capability would be inappropriate and misleading.

If standards are necessary to make comparison they should be based on data that represent the specific population that is being compared. For example, when comparing running economy in elite distance runners the appropriate standard would be that generated from prior data collected from elite distance runners. As more and more elite distance runners are tested the amount of available data will increase, so allowing periodic re-estimation of the standard, which would thus become more representative of the population being compared. Many institutions already have a wealth of data that could, if scaled correctly, be used to generate standards on many specific populations on many physiological variables, not just maximal and sub-maximal $\dot{V}O_2$. After validation, these specific standards could be published, if it was thought of interest to others.

Chapter 9

CONCLUSION

The purpose of these four studies was to investigate the use of the ratio standard and non-linear allometric modelling to adjust for body size, and other physiological and performance measures, in the comparison of aerobic capabilities of men and women.

The use of the ratio standard was an inappropriate technique for scaling values of maximal and sub-maximal $\dot{V}O_2$ as it failed to remove the influence of body size. Moreover, the ratio standard was found to distort the data and this was especially so where the differences in body size were marked. At times the distortion of the data was so great that differences were artificially created between groups (e.g. comparison of $\dot{V}O_{2\,max}$ between distance-runners and heavyweight rowers in study **2**).

Non-linear allometric modelling was an appropriate technique for scaling sub-maximal and maximal $\dot{V}O_2$ as it rendered values independent of body size and correctly modelled the multiplicative error, often reported in physiological data of this type. However, the variation in body size exponents identified from the four studies agrees with the premise of Darveau *et al.* (2002) that no universal exponent, relating $\dot{V}O_2$ with body size, exists.

Further to the use of non-linear allometric modelling, no gender difference in sub-maximal $\dot{V}O_2$ was identified. The conflicting findings in the published literature as to the gender difference in sub-maximal $\dot{V}O_2$ (running economy) are most likely due to the inappropriate use of the ratio standard to account for the influence of body size.

The estimated gender difference in $\dot{V}O_{2\,max}$ depended on the choice of body size variable: body mass or fat free mass. In preference to body mass, the use of fat free mass was recommended as it removed the within-participant and gender differences in body composition. Using fat free mass, the gender difference (95 % C. I.) in $\dot{V}O_{2\,max}$ was 9.6 % (1.0, 19.0) in sub-elite distance-runners (study **1**) and 15.3 % (11.5, 19.2) in International standard endurance athletes (study **2**). After accounting for differences in body size, age and physical activity no gender difference in $\dot{V}O_{2\,max}$ was found in older participants aged between 55 – 86 years (study **3**).

Although more valid than body mass as the body measure used in scaling values for $\dot{V}O_{2\,max}$, the measurement of fat free mass is plagued by lack of reliability. Although prohibitively expensive, the advent of new and validated technology, such as magnetic resonance imaging and computerised tomography, more accurate estimates of fat free mass and skeletal muscle mass are now available. Therefore, it is recommended that, where possible, future investigation into gender differences in $\dot{V}O_{2\,max}$ should take advantage of the extra sensitivity offered by these more accurate measures of body size.

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APPENDICES

Appendix 2·1

Translation - Sarrus and Rameaux (1839)

Report of a paper addressed to the Royal Academy of Medicine by Messrs. Sarrus, Professor of Mathematics at the Faculty of Sciences, Strasbourg, and Rameaux, Doctor of Medicine and of Sciences. (*Academy members*: Messrs. Robiquet and Thillaye, Spokesman.)

"Gentlemen, the authors of the paper of which we have come to give you an account establish in principle that true physiology stems only form the time when physical sciences were cultivated successfully enough to give it definite support, and they consider that the subsequent developments of this science will be the necessary consequences of the intelligent care which will be devoted to apply to it, within appropriate limits and with proper discernment, this mass of new discoveries which enriches daily the various branches of natural philosophy.

Driven by the wish to extend the knowledge of physiology, Messrs. Sarrus and Rameaux have decided to address successively the various questions to which a sufficiency of data and present analytical resources allow the making of a calculation with some semblance of success.

Breathing and circulation are the subject of the first paper they have addressed to you, in the form of a proposition. Here is the problem to which they have sought a solution: "In vertebral animal belonging to the same species and differing from each other only in dimensions, these (dimensions) *regulate* the volume of breathing organs and the number of intakes of breadth, the volume of the heart and the number of its beats, in such a way that if these things are known about an animal, they can be approximately predicted in another of the same species, provided that the relative dimensions of the two animals are known."

Having arrived at the solution, it can be summarised in two words (deux mots).

Between animals of the same species in a normal state and differing from each other only in volume, the number of breath inhalations and of heartbeats are in inverse ratio of the square root of similar animals that are compared: this is what is expressed in the formula $\frac{n'}{n}=\sqrt{\frac{d}{d'}}$; as to the respective volumes of the organs, their relationship is proportionate to the square root of the fifth power of the similar dimensions indicated by the formula $\frac{\mathrm{C}+y}{\mathrm{V}}=\frac{d,^3}{d^2}\sqrt{\frac{d,}{d}}$.

An indisputable geometric proposition, a generally accepted physical law, and some more or less well recorded physiological facts, form the bases for the demonstration given by Messrs. Sarrus and Rameaux. In citing one or another, just like the observations that flow more or less directly from them, your Academy representatives thought that they would provide you with an exact and concise idea of the work you asked them to examine.

Here then are the bases, which support the work we are discussing:

1. Between two similar polyhedrons, their volume are as cubes, and the surfaces as the squares of the similar sides.
2. All other things being equal, bodies of the same nature lose at each moment the quantities of heat which are proportionate to the extent of their unrestricted surface.

3. In animals of the same species, considered to be in a normal state and place in identical conditions, the quantities of heat developed in a given time are proportionate to the quantities of oxygen absorbed in the act of breathing, or indeed are also proportionate to the volume of air inhaled during the same time; admitting however that the air introduced into the lungs with each inhalation leaves there the same proportion of its oxygen.

If we now accept that the animals' temperature is constant, it is to recognise that with them there is a perfect equality between the heat which they produce and that which they releases. Now, as the loss is proportionate to the unrestricted surfaces and these are as the square of similar sides, it must be the cases that the quantities of oxygen absorbed or, to put this another way, that the heat produced on the one hand and lost on the other, are as the square of corresponding dimensions of the animals compared, an essential condition and which can be met in several ways;

1. It is met by accepting that for animals that, in a given period, breathe the same number of times, the lung capacities are in relationship with the extent of the surface of their bodies, in other words as the square of corresponding dimensions. Indeed, if their stature is in the ratio 1:2 their surface area will be as 1 is to 4, numbers that also represent the quantity of heat that they lose in the same given time $v{:}v' \therefore d^3{:}d_,^{\,2}$.
2. The same result is still achieved by supposing that the lung capacities are proportionate to the volume of the body of the animals; but then the number of inhalations must be in inverse proportion to the similar dimensions. Thus, keeping to same given data as previously, if the statures are 1 and 2, the volumes of the bodies and therefore the lung capacities will be as 1:8, whilst the unrestricted surfaces and consequently the causes of cooling down will be only in ratio of 1 to 4. That being the case it is obvious that the small animal will conserve its temperature, as we have suggested, only if the number of its inhalations is, in the same given time, double that of an animal eight times its volume. $v{:}c \therefore d^3{:}d_,^{\,3}$.

Each of these two solutions taken separately will thus suffice to account for the stability of the animals' temperature; neither of them is, however, borne out by observation. Indeed, with young animals the number of inhalations is greater than those in adults. Thus the extent of their lung capacity is in a lesser ratio than that of the square of similar dimensions by the same ratio, since with the young animal the number of inhalations, although greater, is not however double that of an adult; from which it must be concluded that the volume of its lungs is in a proportion greater than the cube of the dimensions of the same designation.

Since proper philosophy does not accept an explanation which has not been borne out by experience, we recognise that neither of the two aforesaid solutions are the absolute expression of what happens in nature. However, if they do not positively reveal nature's method to us, they do at least indicate the limits in which are compromised the two elements of which it is composed, on the one hand the extent of lung capacity and on the other the number of inhalations. The former, for the smallest animal, must be greater than the cube and less than the square of the corresponding dimensions. Now, if in the case of proportionality to the cube it is c, it will have to undergo an increase (y for example). Consequently, it will be in reality $(c + y)$.

As to the inhalations, without being double they must nonetheless exceed, in the same given time, those of a larger animal; so that if for the latter this number is n it will thus be $(n + y)$.

The product of the factors $(c + y)$ and $(n + x)$ represents the quantity of heat developed or the volume of oxygen absorbed: a volume which must moreover be equal to the indicated to us by either of the solutions already obtained. This condition provides the authors of this paper with an equation $(c+y)(n+x)=nv'$ (a) which, incorporating the two unknowns x and y, would leave the problem unresolved if a new given introduced into the calculation did not yield the method of finding the value of one of these quantities commensurate with the other. Here is how Messr. Sarrus and Rameaux have obtained this new given: they have accepted that the increase in y in the lung capacity of the smallest animal being the rise in x in the number of its inhalations in the same ratio as $c{:}u$, from which $y{:}x::c{:}n$ and $y=\frac{cx}{n}$. We quote, moreover, the grounds which made the authors decide to choose this relationship in preference to any other which would have been just as capable of being substituted for it.

"*When nature can achieve an objective by several means, it never employs just one of them up to its limits, it makes them contribute in a way that each of these means is directed to produce an equal share of the total effect.*"

Once this hypothesis is accepted, the solutions given by Messrs. Sarrus and Rameaux are indisputable, since they are the instantaneous deduction of a very simple calculation which consists in eliminating from equation (a).

$$(\mathrm{a})(c+y)(n+x)=nv'$$

the quantities $(c + y)$ and $(n + x)$; which is done by substituting for c, v or y their value deduced from the three proportions already indicated:

$$v{:}c::d^3{:}d,^3$$

$$v{:}v'::d^2{:}d,^2$$

$$y{:}x{:}c^2::n,^2$$

Working this way you effectively arrive at

$$\frac{n'}{n}=\sqrt{\frac{d}{d'}} \text{ and } \frac{c+y}{v}=\frac{d,^2}{d^2}\sqrt{\frac{d'}{d}}$$

the formulated results quoted at the start of this report

It is left to us to show how the equations which, with two animals of different dimensions, express on the one hand the relationship existing between the number of inhalations that they make in the same given time, and establish on the other hand the relation which exists between the extent of their lung capacity, enabling also a knowledge, in the same circumstance, of what is the connection, be it the number of their heartbeats, be it between the respective volumes of this organ.

We quote the principles on which the authors of this paper have relied: "In animals of the same species the blood, at its passage in the lungs, is permeated with an equal quantity of oxygen; in other words the same quantity of blood absorbs the same quantity of oxygen. Now, so that the absorbed oxygen shall be proportionate to the squares of the dimensions of the animals, it is necessary that the lungs receive a dose of blood in relation to the volume of oxygen that has to be absorbed. Therefore the heart must pump at a given moment quantities of blood proportionate to the squares of the animals' dimensions."

Here, as with breathing, this condition can be met in three different ways:

1. The heart capacities are between themselves like the squares of the dimensions of the compared animals or:
2. The number of pulsations is in inverse ratio to these same dimensions or:
3. The capacities and the number of pulsations are combined so as to achieve the same objective.

The third method is the one that Messrs. Sarrus and Rameaux suppose to have been employed by nature; and, to follow them, each of the two elements contribute to it equally.

In comparing this data with that used to resolve the problems concerning breathing, it will be seen that there is perfect identity between them. Therefore the definitive results must also be identical and formulated in the same terms. That indeed is what happened.

It remains for us to assess the merit and usefulness of the work we have tried to give you and understanding, inasmuch at least as it was included in the paper on which we were asked to make a report to you. The reasoning which links between the various parts of this work are most unlikely to be contested; we would wish that it were possible to say the same about the principles on which these reasonings rely; in other words, that the following could be viewed as indisputable truths:

1. That the heat developed by animals has as its unique source the oxygen that they absorb in the act of inhalation;
2. That in large and small animal of the same species the fraction of oxygen absorbed at each inhalation is constant;
3. That there is a proportionality between large and small inhalations made in a given time by animals of the same species, but of different stature;
4. Lastly that nature, just as Messrs. Sarrus and Rameaux have claimed, has combined capacity and inhalations or capacity and heartbeats, contribute equally to the effect produced. Now this assertion is possible, perhaps probable, but not demonstrated; and here it would be all the more important that it should be, for it is that alone which would clear away the uncertainty about the problem which had to be resolved.

Let us add that a hypothetical determination is of little importance when it addresses questions on which it is easy, and in the end always indispensable, to consult experience and observation.

It would doubtless be all too easy to add further objections to those already made, but they appeared sufficient to convince your Academy representatives that the premises for the work of Messr. Sarrus and Rameaux do not have enough certitude to make it possible to accept as unquestionable truths the consequences that they have deduced from them: despite these criticisms, however, the paper which these gentlemen have addressed to you seems to us to be worthy, if only for the relationship in the way the ideas are connected, of being honorably placed in your archives."

Adopted by the Academy.

Appendix 3·1

Anthropometric reproducibility.

Anthropometric reprdoucibility.

Investigator: Patrick Johnson

Male (n = 8)

Test 1

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
M1	29.6	60.70	1.698	3.1	5.8	6.3	6.2	21.4	8.8
M2	20.5	73.95	1.905	3.4	9.2	9.1	9.9	31.6	13.3
M3	27.7	64.80	1.686	4.0	8.2	10.8	15.0	38.0	15.6
M4	22.9	79.65	1.792	3.5	14.6	12.2	15.3	45.6	17.8
M5	23.8	92.75	1.770	5.1	9.9	14.6	30.6	60.2	21.1
M6	20.9	76.00	1.802	4.8	7.6	8.9	19.6	40.9	16.4
M7	24.2	58.55	1.733	2.5	4.4	8.0	10.0	24.9	10.5
M8	29.9	61.25	1.673	2.8	6.7	7.3	8.5	25.3	10.7
Mean	24.9	70.96	1.757	3.7	8.3	9.7	14.4	36.0	14.3
SD	3.7	11.81	0.077	0.9	3.1	2.7	7.9	13.0	4.2

Test 2

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
M1	29.6	60.25	1.708	3.0	5.4	6.0	6.7	21.1	8.6
M2	20.5	74.55	1.908	3.7	9.8	8.8	11.0	33.3	14.0
M3	27.8	65.60	1.685	4.2	7.3	10.5	14.8	36.8	15.2
M4	22.9	79.50	1.800	4.1	14.2	12.3	19.0	49.6	18.8
M5	23.8	93.95	1.779	4.2	12.8	13.1	33.3	63.4	21.8
M6	20.9	75.85	1.803	5.0	10.2	8.7	18.2	42.1	16.8
M7	24.2	58.35	1.743	2.5	4.6	7.8	8.0	22.9	9.5
M8	29.9	61.00	1.679	2.7	6.9	7.1	6.0	22.7	9.4
Mean	25.0	71.13	1.7631	3.7	8.9	9.3	14.6	36.5	14.3
SD	3.7	12.19	0.0764	0.9	3.4	2.5	9.1	14.9	4.8

Anthropometric reprdoucibility.

Investigator: Patrick Johnson

Female (n = 8)

Test 1

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
F1	20.7	52.75	1.664	3.9	11.9	7.5	8.0	31.3	20.2
F2	20.8	62.50	1.693	5.6	14.4	12.2	12.7	44.9	25.3
F3	20.5	75.70	1.783	9.3	21.1	11.7	16.8	58.9	29.2
F4	22.8	53.55	1.561	5.8	11.6	8.2	12.4	38.0	22.9
F5	20.3	67.20	1.755	9.7	18.7	12.8	15.6	56.8	28.7
F6	21.4	68.90	1.784	9.8	24.6	12.8	17.7	64.9	30.6
F7	22.3	60.65	1.639	7.4	20.5	9.6	7.0	44.5	25.2
F8	21.5	69.00	1.760	7.4	17.2	11.8	12.7	49.1	26.6
Mean	21.3	63.78	1.705	7.4	17.5	10.8	12.9	48.6	26.1
SD	0.9	7.97	0.080	2.2	4.6	2.1	3.9	11.2	3.4

Test 2

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
F1	20.7	52.65	1.667	5.0	11.7	7.2	10.8	34.7	21.7
F2	20.8	62.60	1.686	4.9	14.9	11.0	15.5	46.3	25.7
F3	20.5	75.75	1.782	10.9	18.6	11.4	20.4	61.3	29.8
F4	22.8	53.85	1.566	4.4	10.7	8.8	8.8	32.7	20.8
F5	20.3	67.95	1.745	7.4	19.3	12.5	12.5	51.7	27.3
F6	21.5	69.35	1.781	8.6	22.2	12.7	17.5	61.0	29.7
F7	22.3	60.80	1.645	7.6	18.8	9.9	5.2	41.5	24.2
F8	21.5	70.35	1.767	6.8	17.0	11.5	14.3	49.6	26.7
Mean	21.3	64.16	1.705	7.0	16.7	10.6	13.1	47.4	25.7
SD	0.9	8.16	0.077	2.2	4.0	1.9	4.9	10.8	3.3

Anthropometric reprdoucibility.

Investigator: Prof. Edward Winter

Male (n = 8)

Test 1

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
M1	29.6	60.95	1.700	3.0	5.2	6.2	6.0	20.4	8.2
M2	20.5	73.60	1.904	2.6	9.0	8.5	9.5	29.6	12.6
M3	27.7	64.80	1.682	3.8	7.1	10.6	15.2	36.7	15.1
M4	22.9	79.60	1.787	3.0	14.0	12.5	16.1	45.6	17.8
M5	23.8	92.50	1.766	3.4	10.0	14.9	33.5	61.8	21.5
M6	20.9	75.90	1.795	4.7	10.8	9.1	20.0	44.6	17.5
M7	24.2	58.55	1.729	2.0	4.7	8.0	8.7	23.4	9.8
M8	29.9	60.85	1.669	2.6	6.6	6.9	7.2	23.3	9.7
Mean	24.9	70.84	1.754	3.1	8.4	9.6	14.5	35.7	14.0
SD	3.7	11.74	0.077	0.8	3.1	2.9	9.1	14.3	4.7

Test 2

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
M1	29.6	60.50	1.705	2.5	5.6	6.0	5.3	19.4	7.6
M2	20.5	74.50	1.902	2.9	9.4	8.6	10.5	31.4	13.3
M3	27.8	65.55	1.677	3.6	7.3	10.7	16.7	38.3	15.6
M4	22.9	79.45	1.799	3.0	14.5	12.0	18.5	48.0	18.4
M5	23.8	93.85	1.772	2.9	11.7	13.0	35.3	62.9	21.7
M6	20.9	75.85	1.798	4.0	10.3	9.2	18.8	42.3	16.8
M7	24.2	58.35	1.734	2.1	4.3	8.0	8.1	22.5	9.3
M8	29.9	60.95	1.668	2.3	6.6	6.9	6.0	21.8	9.0
Mean	25.0	71.13	1.757	2.9	8.7	9.3	14.9	35.8	14.0
SD	3.7	12.13	0.078	0.6	3.4	2.4	9.9	15.1	5.0

Anthropometric reprdoucibility.

Investigator: Prof. Edward Winter

Female (n = 8)

Test 1

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
F1	20.7	52.75	1.659	4.4	12.6	6.9	8.2	32.1	20.6
F2	20.8	62.30	1.690	5.1	13.9	11.1	11.7	41.8	24.3
F3	20.5	75.55	1.777	11.0	18.9	12.6	17.2	59.7	29.4
F4	22.8	53.50	1.567	5.8	11.5	8.4	11.2	36.9	22.5
F5	20.3	67.15	1.743	11.0	22.4	13.1	11.8	58.3	29.0
F6	21.4	69.00	1.779	11.0	25.5	14.0	18.9	69.4	31.6
F7	22.3	60.65	1.635	6.6	20.2	11.4	5.7	43.9	25.0
F8	21.5	68.95	1.764	8.8	17.0	10.9	12.5	49.2	26.6
Mean	21.3	63.73	1.702	8.0	17.8	11.1	12.2	48.9	26.1
SD	0.9	7.96	0.077	2.8	4.9	2.4	4.3	12.7	3.7

Test 2

Subject	Age	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailiac (mm)	Skinfolds (mm)	Body fat (%)
F1	20.7	52.65	1.658	4.2	10.4	6.8	12.4	33.8	21.3
F2	20.8	62.55	1.675	5.1	14.7	11.2	15.9	46.9	25.9
F3	20.5	75.60	1.778	12.0	18.2	14.1	23.2	67.5	31.2
F4	22.8	53.85	1.563	5.2	12.4	8.8	9.4	35.8	22.1
F5	20.3	67.55	1.739	11.1	19.8	13.0	15.5	59.4	29.3
F6	21.5	69.00	1.779	11.0	25.5	14.0	18.9	69.4	31.6
F7	22.3	60.75	1.639	8.4	19.2	10.3	4.9	42.8	24.6
F8	21.5	70.35	1.765	6.9	17.5	11.6	12.9	48.9	26.5
Mean	21.3	64.04	1.700	8.0	17.2	11.2	14.1	50.6	26.6
SD	0.9	8.08	0.078	3.1	4.7	2.6	5.6	13.6	3.9

Appendix 3·2

Maximal oxygen uptake reproducibility.

Maximal oxygen uptake reproducibility.

	VO_{2max} ($l\cdot min^{-1}$)		RER		Maximum HR ($b\cdot min^{-1}$)		Blood lactate ($mmol\cdot l^{-1}$)		Run time (secs)	
Subject	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
1	3.85	3.92	1.05	1.08	201	199	9.1	8.4	760	770
2	4.08	4.18	1.12	1.10	191	189	10.4	10.8	590	575
3	4.05	4.28	1.07	1.09	196	203	10.5	8.2	630	680
4	4.27	4.25	1.04	1.07	184	182	9.6	10.5	525	530
5	4.87	4.87	1.04	1.04	198	197	6.8	6.5	545	510
6	4.70	4.98	1.17	1.12	180	176	5.7	6.9	590	630
Mean	4.30	4.41	1.08	1.08	192	191	8.7	8.5	607	616
SD	0.40	0.42	0.05	0.03	8	11	2.0	1.8	84	98

Appendix 3·3

Gas meter calibration example

Gas meter calibration example

Date: 97·597

Flow rate ($l \cdot min^{-1}$): 321

Measured (litres)	Dry gas reading (litres)					Mean (litres)	Temp (°C)	*r*
	1	2	3	4	5			
14	14.1	14.0	14.2	14.0	14.0	14.1	21.1	
35	35.2	35.3	35.3	35.0	35.0	35.1	20.9	
70	69.6	69.8	70.0	70.4	69.8	69.9	21.0	
105	105.0	105.0	106.0	106.0	105.1	105.4	21.0	
140	141.0	139.5	140.9	140.0	139.9	140.3	20.3	1.000

Appendix 3·4

Treadmill calibration

Treadmill calibration

Date: 97·285

Belt length (m): 3.94

Sample time (Hz): 10

Subjects mass (kg): 52.1

Indicated speed		Sample time (s)					Mean	Actual speed	
$m \cdot s^{-1}$	$km \cdot h^{-1}$	1	2	3	4	5	(s)	$m \cdot s^{-1}$	$km \cdot h^{-1}$
2.69	9.7	14.52	14.51	14.53	14.54	14.54	14.53	2.71	9.8
3.14	11.3	12.48	12.49	12.52	12.49	12.45	12.49	3.16	11.4
3.58	12.9	10.93	10.92	10.91	10.91	10.90	10.91	3.61	13.0
4.03	14.5	9.72	9.74	9.72	9.74	9.73	9.73	4.05	14.6

Subjects mass (kg): 68.5

Indicated speed		Sample time (s)					Mean	Actual speed	
$m \cdot s^{-1}$	$km \cdot h^{-1}$	1	2	3	4	5	(s)	$m \cdot s^{-1}$	$km \cdot h^{-1}$
2.69	9.7	14.43	14.41	14.43	14.43	14.40	14.42	2.73	9.8
3.14	11.3	12.45	12.40	14.40	12.40	12.40	12.41	3.17	11.4
3.58	12.9	10.95	10.94	10.94	10.93	10.93	10.94	3.60	13.0
4.03	14.5	9.70	9.70	9.70	9.70	9.69	9.70	4.06	14.6

Treadmill calibration

Subjects mass (kg): 85.0

Indicated speed		Sample time					Mean	Actual speed	
$m \cdot s^{-1}$	$km \cdot h^{-1}$	(s)					(s)	$m \cdot s^{-1}$	$km \cdot h^{-1}$
		1	2	3	4	5			
2.69	9.7	14.37	14.40	14.40	14.39	14.42	14.40	2.74	9.9
3.14	11.3	12.52	12.52	12.52	12.51	12.51	12.52	3.15	11.3
3.58	12.9	10.92	10.91	10.91	10.89	10.92	10.91	3.61	13.0
4.03	14.5	9.75	9.73	9.73	9.73	9.75	9.74	4.05	14.6

Appendix 4·1

Study 1: Informed consent

INFORMED CONSENT

DE MONTFORT
UNIVERSITY
BEDFORD

INFORMED CONSENT FORM

1 Purpose To assess possible gender differences in maximal oxygen uptake in distance-runners.

2 Procedures The laboratory procedures include:

- assessment of stature and body mass
- estimation of body fat % using skin-fold measurements
- determination of maximal oxygen uptake via a treadmill run to volutional exhaustion.

This exercise is strenuous and might produce feelings of nausea or giddiness.

3 Queries I will be pleased to answer any queries that you might have.

4 Withdrawal You are free at any time to withdraw consent and stop participating.

5 Confidentiality Your identity will be strictly confidential and all data will be anonymous.

6 Consent I . . . . have read and understood the information on this form and agree to take part in the study.

Signed: . . . . Date: . . . .

Paddy Johnson
Home:01234 447842
Work: 01234 793378

Appendix 4·2

Study 1: Descriptive and study criteria data.

Study 1: Descriptive and study criteria data.

Male (n = 17)

Subject	Age (yrs)	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailliac (mm)	Sum (mm)	Fat (%)	FFM (kg)	VO_{2max} ($l \cdot min^{-1}$)	Experience (yrs)	Injury	Full training
1	16.8	63.8	1.709	5.3	11.1	10.1	20.9	47.4	18.6	51.9	4.45	4	no	yes
2	18.0	58.8	1.801	3.2	6.4	6.3	7.5	23.4	10.1	52.8	4.24	6	no	yes
3	25.9	68.6	1.702	4.3	10.8	8.4	8.0	31.5	13.3	59.5	4.78	3	no	yes
4	21.1	75.2	1.936	3.0	4.8	8.0	7.9	23.7	9.9	67.8	5.73	10	no	yes
5	27.8	62.3	1.710	2.8	6.8	7.1	7.8	24.5	10.3	55.8	4.69	8	no	yes
6	19.5	65.8	1.765	3.6	8.0	8.3	10.5	30.4	13.2	57.1	5.00	5	no	yes
7	28.2	68.2	1.807	5.0	11.0	12.1	15.5	43.6	17.2	56.5	4.69	4	no	yes
8	21.1	74.6	1.849	6.7	13.0	11.6	16.2	47.5	18.2	61.0	4.98	5	no	yes
9	19.5	69.3	1.757	4.2	7.6	8.2	12.0	32.0	13.8	59.7	4.87	3	no	yes
10	24.7	69.3	1.744	3.8	7.8	11.1	19.3	42.0	16.8	57.7	4.28	3	no	yes
11	19.6	78.0	1.910	3.0	5.2	6.8	5.0	20.0	8.3	71.5	6.41	9	no	yes
12	34.6	67.9	1.735	3.1	4.6	7.5	8.0	23.2	9.7	61.3	5.03	23	no	yes
13	25.7	69.5	1.828	2.8	4.8	6.8	5.0	19.4	7.6	64.2	5.74	4	no	yes
14	21.6	75.6	1.788	3.3	4.5	8.4	6.8	23.0	9.6	68.3	5.84	8	no	yes
15	25.8	76.8	1.897	3.1	5.9	6.9	10.4	26.3	11.2	68.2	5.68	9	no	yes
16	20.9	70.0	1.788	3.8	8.8	8.8	13.8	35.2	14.6	59.8	5.01	7	no	yes
17	23.4	69.3	1.810	3.1	6.1	9.3	7.8	26.3	11.2	61.5	5.09	10	no	yes
Mean	23.2	69.6	1.796	3.8	7.5	8.6	10.7	30.6	12.6	60.9	5.09	7		
SD	4.5	5.2	0.071	1.1	2.6	1.8	4.8	9.4	3.5	5.6	0.60	5		

Study 1: Descriptive and study criteria data.

Male (n = 17)

Subject	Age (yrs)	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailliac (mm)	Sum (mm)	Fat (%)	FFM (kg)	VO_{2max} ($l \cdot min^{-1}$)	Experience (yrs)	Injury	Full training
1	16.8	63.8	1.709	5.3	11.1	10.1	20.9	47.4	18.6	51.9	4.45	4	no	yes
2	18.0	58.8	1.801	3.2	6.4	6.3	7.5	23.4	10.1	52.8	4.24	6	no	yes
3	25.9	68.6	1.702	4.3	10.8	8.4	8.0	31.5	13.3	59.5	4.78	3	no	yes
4	21.1	75.2	1.936	3.0	4.8	8.0	7.9	23.7	9.9	67.8	5.73	10	no	yes
5	27.8	62.3	1.710	2.8	6.8	7.1	7.8	24.5	10.3	55.8	4.69	8	no	yes
6	19.5	65.8	1.765	3.6	8.0	8.3	10.5	30.4	13.2	57.1	5.00	5	no	yes
7	28.2	68.2	1.807	5.0	11.0	12.1	15.5	43.6	17.2	56.5	4.69	4	no	yes
8	21.1	74.6	1.849	6.7	13.0	11.6	16.2	47.5	18.2	61.0	4.98	5	no	yes
9	19.5	69.3	1.757	4.2	7.6	8.2	12.0	32.0	13.8	59.7	4.87	3	no	yes
10	24.7	69.3	1.744	3.8	7.8	11.1	19.3	42.0	16.8	57.7	4.28	3	no	yes
11	19.6	78.0	1.910	3.0	5.2	6.8	5.0	20.0	8.3	71.5	6.41	9	no	yes
12	34.6	67.9	1.735	3.1	4.6	7.5	8.0	23.2	9.7	61.3	5.03	23	no	yes
13	25.7	69.5	1.828	2.8	4.8	6.8	5.0	19.4	7.6	64.2	5.74	4	no	yes
14	21.6	75.6	1.788	3.3	4.5	8.4	6.8	23.0	9.6	68.3	5.84	8	no	yes
15	25.8	76.8	1.897	3.1	5.9	6.9	10.4	26.3	11.2	68.2	5.68	9	no	yes
16	20.9	70.0	1.788	3.8	8.8	8.8	13.8	35.2	14.6	59.8	5.01	7	no	yes
17	23.4	69.3	1.810	3.1	6.1	9.3	7.8	26.3	11.2	61.5	5.09	10	no	yes
Mean	23.2	69.6	1.796	3.8	7.5	8.6	10.7	30.6	12.6	60.9	5.09	7		
SD	4.5	5.2	0.071	1.1	2.6	1.8	4.8	9.4	3.5	5.6	0.60	5		

Study 1: Descriptive and study criteria data.

Female (n = 17)

Subject	Age (yrs)	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailliac (mm)	Sum (mm)	Fat (%)	FFM (kg)	VO_{2max} ($l \cdot min^{-1}$)	Experience (yrs)	Injury	Full Training
1	16.5	47.4	1.698	4.6	7.2	7.1	7.7	26.6	17.7	39.0	2.84	4	no	yes
2	17.0	45.2	1.663	4.4	7.2	6.6	8.8	27.0	20.8	35.8	2.76	4	no	yes
3	22.1	68.2	1.639	7.3	18.8	12.5	18.7	57.3	28.8	48.6	3.90	12	no	yes
4	22.6	53.4	1.576	7.1	14.5	18.9	13.0	53.5	27.8	38.6	2.96	12	no	yes
5	16.5	58.4	1.547	8.3	17.4	9.5	19.8	55.0	27.4	42.4	3.37	3	no	yes
6	32.0	49.9	1.582	4.2	15.1	10.0	6.8	36.1	24.2	37.8	3.19	12	no	yes
7	23.2	54.2	1.584	4.4	12.2	11.1	10.1	37.8	22.9	41.8	3.34	7	no	yes
8	19.5	61.0	1.605	5.4	14.2	10.5	17.1	47.2	25.3	45.6	3.49	4	no	yes
9	21.5	60.0	1.650	4.4	10.0	8.8	14.3	37.5	22.8	46.3	4.25	10	no	yes
10	33.5	56.3	1.624	2.8	8.9	6.0	5.6	23.3	16.2	47.1	3.25	12	no	yes
11	18.0	60.7	1.821	3.8	8.4	5.8	7.4	25.4	17.1	50.3	3.83	6	no	yes
12	30.2	61.7	1.608	6.8	14.6	9.6	12.4	43.4	24.8	46.4	3.36	4	no	yes
13	16.6	48.7	1.623	4.6	14.6	7.8	9.4	36.4	21.9	38.0	3.05	6	no	yes
14	27.4	59.3	1.708	4.4	10.6	10.0	8.6	33.6	21.2	46.7	3.27	14	no	yes
15	24.7	52.0	1.591	3.8	11.6	7.9	5.0	28.3	18.8	42.2	2.98	15	no	yes
16	36.2	64.9	1.698	7.2	18.8	9.3	9.6	44.9	25.3	48.4	3.61	10	no	yes
17	20.2	47.6	1.695	4.5	9.0	7.1	11.5	32.1	20.6	37.8	2.85	5	no	yes
Mean	23.4	55.8	1.642	5.2	12.5	9.3	10.9	38.0	22.6	43.1	3.31	8		
SD	6.5	6.6	0.068	1.6	3.8	3.1	4.6	11.0	3.9	4.6	0.41	4		

Appendix 4·3

Study 1: Maximal oxygen uptake data.

Study 1: Maximal oxygen uptake individual data.

Male (n = 17)

Subject	Mass	FFM	Maximal oxygen uptake						
	(kg)	(kg)	(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·BM$^{-0.94}$·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·FFM$^{-0.98}$·min^{-1})
1	63.0	51.3	4.45	70.6	277	199	90.9	86.8	95.0
2	59.2	53.2	4.24	71.6	275	199	91.9	79.7	87.3
3	69.5	60.3	4.78	68.8	279	199	89.1	79.3	87.2
4	75.2	67.8	5.73	76.2	317	224	99.2	84.6	93.2
5	61.6	55.3	4.69	76.1	297	213	97.9	84.9	93.1
6	65.6	56.9	5.00	76.2	303	217	98.4	87.8	96.4
7	68.2	56.5	4.69	68.8	277	198	89.0	83.1	91.1
8	74.6	61.0	4.98	66.8	277	196	86.8	81.6	89.7
9	69.3	59.7	4.87	70.3	285	203	91.0	81.5	89.6
10	69.3	57.7	4.28	61.8	250	178	80.0	74.2	81.5
11	78.0	71.5	6.41	82.2	346	244	107.2	89.6	98.9
12	67.9	61.3	5.03	74.1	298	213	95.8	82.0	90.2
13	69.5	64.2	5.74	82.6	335	239	107.0	89.4	98.4
14	74.7	67.5	5.84	78.2	325	230	101.7	86.5	95.3
15	76.8	68.2	5.68	74.0	310	219	96.4	83.3	91.8
16	70.0	59.8	5.01	71.6	291	207	92.7	83.8	92.1
17	68.8	61.1	5.09	74.0	299	213	95.8	83.4	91.6
Mean	69.5	60.8	5.09	73.2	296	211	94.8	83.6	91.9
SD	5.3	5.6	0.60	5.3	24	17	7.0	3.9	4.3
SEM	1.3	1.4	0.15	1.3	6	4	1.7	0.9	1.1

Study 1: Maximal oxygen uptake individual data.

Female (n = 17)

Subject	Mass (kg)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.75} \cdot min^{-1}$)	($ml \cdot BM^{-0.94} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-0.98} \cdot min^{-1}$)
1	49.2	40.5	2.84	57.7	209	153	73.2	70.1	76.4
2	44.2	35.0	2.76	62.4	218	161	78.7	78.8	85.6
3	68.2	48.6	3.90	57.2	230	164	74.0	80.3	87.8
4	51.2	37.0	2.96	57.8	212	155	73.5	80.1	87.0
5	57.0	41.4	3.37	59.1	224	162	75.7	81.4	88.7
6	49.9	37.8	3.19	63.9	232	170	81.1	84.3	91.7
7	54.2	41.8	3.34	61.6	230	167	78.6	79.9	87.1
8	60.5	45.2	3.49	57.7	223	161	74.1	77.2	84.3
9	62.2	48.0	4.25	68.3	267	192	87.9	88.5	96.8
10	56.0	46.9	3.25	58.0	219	159	74.2	69.3	75.7
11	60.7	50.3	3.83	63.1	245	176	81.1	76.1	83.3
12	62.5	47.0	3.36	53.8	210	151	69.2	71.5	78.1
13	48.7	38.0	3.05	62.6	226	165	79.4	80.2	87.2
14	59.3	46.7	3.27	55.1	212	153	70.7	70.0	76.4
15	52.0	42.2	2.98	57.3	211	154	72.9	70.6	76.9
16	64.9	48.4	3.61	55.7	221	158	71.8	74.5	81.5
17	47.4	37.6	2.85	60.1	215	158	76.1	75.7	82.3
Mean	55.8	43.1	3.31	59.5	224	162	76.0	77.0	83.9
SD	6.9	4.9	0.41	3.7	15	10	4.6	5.5	6.0
SEM	1.7	1.2	0.10	0.9	4	2	1.1	1.3	1.4

Appendix 5·1

Study 2: Descriptive and maximal oxygen uptake data.

Study 2 - Long distance runners.

Male (n = 10)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.71} \cdot min^{-1}$)	($ml \cdot FFM^{-0.83} \cdot min^{-1}$)
CB	17.9	50.8	1.705	5.6	48.0	4.04	79.5	84.2	291	246	162
MC	31.6	60.0	1.720	12.7	52.4	4.60	76.7	87.8	296	249	171
AD	29.7	68.1	1.740	8.3	62.4	5.47	80.4	87.7	324	271	176
PD	29.2	64.0	1.760	11.2	56.8	5.27	82.3	92.7	325	273	184
SD	23.9	64.0	1.790	7.1	59.4	5.23	81.8	88.0	323	271	176
RF	28.5	61.7	1.740	7.4	57.1	4.68	75.9	81.9	296	249	162
GG	32.8	65.5	1.760	9.8	59.1	4.70	71.8	79.6	285	239	158
JL	18.1	56.4	1.715	7.1	52.4	4.12	73.0	78.6	276	233	154
AP	23.8	63.3	1.760	7.3	58.7	4.70	74.2	80.1	292	245	159
PS	30.4	68.5	1.730	8.9	62.4	5.35	78.1	85.7	315	264	172
Mean	26.6	62.2	1.742	8.5	56.9	4.82	77.4	84.6	302	254	167
SD	5.4	5.4	0.026	2.2	4.7	0.50	3.7	4.6	18	14	10
SEM	1.7	1.7	0.008	0.7	1.5	0.16	1.2	1.4	6	5	3

Study 2 - Long distance runners.

Female (n = 10)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot FFM^{-0.71} \cdot min^{-1}$)	($ml \cdot FFM^{-0.83} \cdot min^{-1}$)
LW	24.0	50.0	1.650	16.9	41.6	2.87	57.4	69.1	209	177	130
NS	17.7	42.2	1.600	17.3	34.9	2.51	59.5	71.9	205	175	131
DS	30.6	49.5	1.600	18.9	40.1	3.24	65.5	80.7	237	201	151
DP	32.3	46.8	1.555	19.1	37.9	3.11	66.5	82.1	236	201	152
AO	17.2	46.5	1.610	11.0	41.3	3.25	70.0	78.6	248	211	147
JH	28.0	57.5	1.690	15.9	48.4	3.98	69.2	82.3	264	222	159
TD	34.3	52.7	1.680	17.0	43.7	3.62	68.7	82.8	254	215	157
AC	20.3	56.3	1.715	16.8	46.8	3.32	59.0	70.9	223	188	136
KB	28.4	51.5	1.600	16.9	42.8	3.14	61.0	73.4	224	190	138
EB	16.3	42.7	1.510	17.8	35.1	2.74	64.2	78.1	221	189	142
Mean	24.9	49.6	1.621	16.8	41.3	3.18	64.1	77.0	232	197	144
SD	6.7	5.2	0.063	2.2	4.5	0.42	4.6	5.2	19	16	10
SEM	2.1	1.6	0.020	0.7	1.4	0.13	1.5	1.6	6	5	3

Study 2 - Middle distance runners.

Male (n = 11)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.71} \cdot min^{-1}$)	($ml \cdot FFM^{-0.83} \cdot min^{-1}$)
AW	22.9	71.6	1.890	9.6	64.7	5.28	73.8	81.6	302	252	165
SB	23.7	70.3	1.830	9.7	63.5	5.62	79.9	88.5	325	272	179
SB	19.6	62.6	1.780	10.6	56.0	4.99	79.7	89.2	312	262	176
EB	18.6	63.4	1.750	9.8	57.2	4.60	72.6	80.4	285	240	159
MB	18.6	60.6	1.720	6.9	56.4	4.98	82.2	88.3	319	268	175
AD	23.8	66.4	1.785	8.9	60.5	5.20	78.3	86.0	313	262	172
MG	20.3	71.3	1.700	9.1	64.8	5.38	75.5	83.0	308	258	168
MH	21.7	71.5	1.860	10.1	64.3	5.34	74.7	83.1	306	255	168
RH	23.3	73.8	1.875	9.0	67.2	5.96	80.8	88.7	334	279	181
AP	19.2	64.4	1.800	NA	NA	4.52	70.2	NA	278	233	NA
JS	21.2	62.6	1.780	10.6	56.0	4.15	66.3	74.2	260	218	146
Mean	21.2	67.1	1.797	9.4	61.0	5.09	75.8	84.3	304	255	169
SD	2.0	4.7	0.062	1.1	4.3	0.52	4.9	4.8	22	18	10
SEM	0.6	1.5	0.020	0.4	1.5	0.16	1.6	1.6	7	6	3

Study 2 - Middle distance runners.

Female (n = 19)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.71} \cdot min^{-1}$)	($ml \cdot FFM^{-0.83} \cdot min^{-1}$)
NT	22.7	62.0	1.718	17.7	51.0	3.72	60.0	72.9	234	197	142
SS	17.0	57.7	1.695	20.6	45.8	3.28	56.9	71.7	217	183	137
US	27.7	56.9	1.685	18.0	46.7	3.56	62.6	76.3	237	200	146
LR	24.5	46.9	1.570	15.5	39.6	3.26	69.5	82.3	247	211	153
RL	16.4	54.4	1.700	16.2	45.5	3.02	55.6	66.3	208	176	126
MN	22.8	53.2	1.600	18.6	43.3	3.70	69.5	85.4	258	218	162
NL	23.3	53.6	1.670	13.3	46.5	3.97	74.1	85.4	276	233	163
LK	18.6	63.3	1.680	20.2	50.5	4.19	66.2	83.0	260	219	161
MK	27.9	55.2	1.685	18.0	45.3	3.50	63.4	77.3	238	201	147
KH	25.8	55.3	1.615	16.9	46.0	3.05	55.2	66.4	207	175	127
BH	26.7	45.7	1.570	17.6	37.6	2.96	64.8	78.7	229	195	145
DG	29.8	52.8	1.610	18.0	43.3	3.47	65.8	80.2	243	206	152
MH	15.1	59.5	1.680	NA	NA	3.44	57.8	NA	223	188	NA
LG	24.6	49.8	1.650	16.9	41.4	3.17	63.7	76.6	231	196	144
HD	32.1	64.2	1.700	17.9	52.7	3.81	59.4	72.3	234	197	141
SB	34.8	56.8	1.690	18.6	46.2	3.30	58.1	71.4	220	186	137

Study 2 - Middle distance runners.

Female (n = 19)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake ($l \cdot min^{-1}$)	($ml \cdot BM^{-1} \cdot min^{-1}$)	($ml \cdot FFM^{-1} \cdot min^{-1}$)	($ml \cdot BM^{-0.67} \cdot min^{-1}$)	($ml \cdot BM^{-0.71} \cdot min^{-1}$)	($ml \cdot FFM^{-0.83} \cdot min^{-1}$)
WW	25.3	58.3	1.740	18.1	47.7	3.87	66.4	81.1	254	214	156
LY	22.6	55.9	1.690	19.4	45.0	3.81	68.2	84.6	257	217	161
Mean	24.3	55.6	1.664	17.7	45.5	3.50	63.2	77.2	238	201	147
SD	5.3	5.0	0.050	1.7	3.9	0.35	5.4	6.2	19	16	12
SEM	1.3	1.2	0.012	0.4	1.0	0.09	1.3	1.6	5	4	3

Study 2 - Lightweight rowers.

Male (n = 13)

Initials	Age	Mass	Stature	Body fat	FFM	Maximal oxygen uptake					
	(yrs)	(kg)	(m)	(%)	(kg)	(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.71}$·min^{-1})	(ml·FFM$^{-0.83}$·min^{-1})
B	33.0	71.8	1.770	16.1	60.2	5.10	71.1	84.7	291	243	169
B	30.0	74.4	1.840	12.1	65.4	5.05	67.9	77.2	281	235	157
G	28.0	73.0	1.780	12.4	63.9	4.90	67.1	76.6	277	231	155
H	31.0	73.3	1.820	11.0	65.2	5.41	73.8	82.9	304	254	168
K	26.0	74.0	1.850	8.7	67.6	5.60	75.7	82.9	313	261	169
L	26.0	71.5	1.800	6.5	66.9	5.32	74.4	79.6	304	254	162
L	33.0	75.0	1.800	12.8	65.4	5.20	69.4	79.6	288	241	161
L	19.0	74.8	1.830	8.5	68.4	5.29	70.8	77.3	294	245	158
M	22.0	73.8	1.855	6.1	69.3	5.50	74.5	79.4	308	257	162
M	30.0	75.4	1.880	13.7	65.1	5.57	73.9	85.6	308	257	173
S	30.0	73.7	1.790	14.3	63.2	5.70	77.3	90.2	320	267	182
CS	34.0	76.1	1.830	10.6	68.0	5.90	77.5	86.7	324	270	177
W	28.0	73.8	1.865	8.2	67.7	5.09	69.0	75.1	285	238	153
Mean	28.5	73.9	1.824	10.8	65.9	5.36	72.5	81.4	300	250	165
SD	4.4	1.3	0.034	3.1	2.5	0.29	3.5	4.5	15	12	9
SEM	1.3	0.4	0.010	0.9	0.7	0.08	1.0	1.3	4	3	2

Study 2 - Lightweight rowers.

Female (n = 12)

Initials	Age	Mass	Sature	Body fat	FFM	Maximal oxygen uptake					
	(yrs)	(kg)	(m)	(%)	(kg)	(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.71}$·min^{-1})	(ml·FFM$^{-0.83}$·min^{-1})
JH	21.6	57.9	1.714	19.5	46.6	3.48	60.1	74.7	229	193	143
CS	28.1	63.9	1.765	18.7	52.0	3.76	58.8	72.4	232	195	141
AN	26.0	58.9	1.690	17.4	48.7	3.59	61.0	73.8	234	197	142
AB	24.9	57.1	1.705	20.2	45.6	3.50	61.3	76.8	233	196	146
NB	27.0	57.2	1.620	19.8	45.8	3.34	58.4	72.9	222	187	139
AB	32.8	59.3	1.597	20.0	47.4	3.67	61.9	77.4	238	201	149
CA	31.0	58.3	1.700	15.8	49.1	3.50	60.0	71.3	230	194	138
TC	28.5	63.3	1.630	23.1	48.7	3.77	59.6	77.4	234	197	149
ND	33.0	61.6	1.630	19.4	49.6	3.85	62.5	77.5	243	205	150
VF	18.1	65.0	1.730	25.1	48.7	3.40	52.3	69.8	207	174	135
LH	24.0	64.3	1.660	23.2	49.3	3.86	60.1	78.2	237	199	151
CH	26.3	57.4	1.715	16.6	47.9	3.70	64.5	77.3	245	207	149
Mean	26.8	60.3	1.680	19.9	48.3	3.62	60.0	75.0	232	195	144
SD	4.4	3.1	0.051	2.8	1.8	0.18	2.9	2.9	10	9	5
SEM	1.3	0.9	0.0	0.8	0.5	0.1	0.9	0.8	3	2	2

Study 2 - Heavyweight rowers.

Male (n = 16)

Initials	Age	Mass	Sature	Body fat	FFM	Maximal oxygen uptake					
	(yrs)	(kg)	(m)	(%)	(kg)	(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.71}$·min^{-1})	(ml·FFM$^{-0.83}$·min^{-1})
B	23.0	92.6	1.940	13.9	79.7	6.03	65.1	75.6	290	240	159
B	26.0	96.6	2.030	15.0	82.1	6.54	67.7	79.6	306	253	168
C	23.0	94.7	1.930	12.2	83.1	6.54	69.1	78.7	310	256	166
F	25.0	90.3	1.905	9.2	82.0	5.55	61.5	67.7	272	225	143
H	22.0	94.3	1.941	11.7	83.3	5.95	63.1	71.5	283	234	151
H	26.0	96.1	1.900	15.3	81.4	6.16	64.1	75.7	289	239	159
HD	23.0	94.6	1.970	9.3	85.8	7.42	78.4	86.5	352	291	184
P	23.0	92.2	1.920	8.9	84.0	6.18	67.0	73.6	298	247	156
P	25.0	103.7	1.950	13.6	89.6	8.11	78.2	90.5	362	298	193
R	33.0	102.0	1.950	9.8	92.0	7.29	71.5	79.2	329	271	170
R	22.0	88.0	1.940	13.8	75.9	6.12	69.5	80.7	305	253	168
GS	23.0	102.5	1.965	10.0	92.3	7.86	76.7	85.2	353	291	183
S	28.0	88.0	1.870	12.4	77.1	5.84	66.4	75.8	291	241	158
GS	20.0	87.5	1.910	7.1	81.3	5.33	60.9	65.6	266	221	138
T	21.0	85.0	1.880	10.4	76.2	5.88	69.2	77.2	300	249	161

Study 2 - Heavyweight rowers.

Male (n = 16)

Initials	Age (yrs)	Mass (kg)	Sature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake (l·min-1)	$(ml \cdot BM^{-1} \cdot min^{-1})$	$(ml \cdot FFM^{-1} \cdot min^{-1})$	$(ml \cdot BM^{-0.67} \cdot min^{-1})$	$(ml \cdot BM^{-0.71} \cdot min^{-1})$	$(ml \cdot FFM^{-0.83} \cdot min^{-1})$
W	27.0	84.3	1.940	9.8	76.0	6.84	81.2	90.0	351	291	187
Mean	24.4	93.3	1.934	11.4	82.6	6.48	69.3	78.3	310	256	165
SD	3.2	6.0	0.038	2.4	5.3	0.82	6.3	7.2	30	25	16
SEM	0.8	1.5	0.010	0.6	1.3	0.20	1.6	1.8	8	6	4

Study 2 - Heavyweight rowers.

Female (n = 28)

Initials	Age (yrs)	Mass (kg)	Stature (m)	Body fat (%)	FFM (kg)	Maximal oxygen uptake					
						(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.71}$·min^{-1})	(ml·FFM$^{-0.83}$·min^{-1})
GB	29.0	77.3	1.730	25.6	57.5	4.36	56.4	75.8	237	197	150
CB	23.9	91.3	1.830	26.9	66.7	5.00	54.8	74.9	243	201	152
MB	30.6	69.6	1.740	20.4	55.4	4.48	64.4	80.9	261	218	159
DB	27.0	76.5	1.800	18.2	62.5	4.28	56.0	68.4	234	195	138
RC	24.4	82.3	1.780	23.8	62.7	4.67	56.8	74.5	243	202	150
LE	26.8	72.9	1.745	21.4	57.3	4.40	60.4	76.8	249	208	152
GK	20.5	97.6	1.920	30.2	68.1	4.42	45.3	64.9	205	169	132
CD	21.0	67.7	1.750	24.3	51.2	4.10	60.6	80.0	243	204	156
JE	29.3	72.4	1.830	17.7	59.6	4.01	55.4	67.3	228	190	134
AE	27.4	67.7	1.830	17.5	55.9	3.65	53.9	65.4	217	182	129
AG	29.1	80.0	1.810	28.0	57.6	4.70	58.8	81.6	249	208	162
CG	24.0	73.7	1.825	25.2	55.1	3.94	53.5	71.5	221	184	141
EH	19.1	68.9	1.745	28.9	49.0	3.72	54.0	76.0	218	183	147
GL	20.0	81.5	1.810	24.2	61.8	3.90	47.9	63.1	204	170	127
KM	34.2	70.9	1.760	22.8	54.7	4.07	57.4	74.4	234	196	146
TM	19.1	73.0	1.735	26.4	53.7	3.87	53.1	72.1	219	182	141
KP	28.2	73.5	1.780	18.6	59.8	4.90	66.7	81.9	275	230	164

Study 2 - Heavyweight rowers.

Female (n = 28)

Initials	Age	Mass	Stature	Body fat	FFM	Maximal oxygen uptake					
	(yrs)	(kg)	(m)	(%)	(kg)	(l·min-1)	(ml·BM^{-1}·min^{-1})	(ml·FFM^{-1}·min^{-1})	(ml·BM$^{-0.67}$·min^{-1})	(ml·BM$^{-0.71}$·min^{-1})	(ml·FFM$^{-0.83}$·min^{-1})
TR	31.0	82.2	1.820	31.8	56.1	4.39	53.4	78.3	229	190	155
RR	31.1	71.3	1.690	23.6	54.5	3.77	52.9	69.2	216	181	136
SS	39.1	74.3	1.850	20.4	59.1	4.11	55.3	69.5	229	191	138
AS	29.8	69.0	1.745	21.7	54.0	4.02	58.3	74.4	236	197	146
KT	27.0	83.8	1.810	24.8	63.0	4.90	58.5	77.8	252	209	157
JT	26.7	74.5	1.840	18.8	60.5	4.50	60.4	74.4	251	209	149
EW	18.7	73.3	1.770	23.9	55.8	3.88	52.9	69.6	218	182	137
SW	22.6	82.9	1.890	22.2	64.5	4.80	57.9	74.5	249	207	151
CH	20.8	67.3	1.815	20.5	53.5	3.81	56.6	71.2	227	190	140
SW	27.5	74.2	1.750	26.6	54.4	4.06	54.8	74.6	227	189	147
EL	21.2	76.3	1.770	23.8	58.1	3.83	50.2	65.9	210	175	131
Mean	26.0	75.9	1.792	23.5	57.9	4.23	55.9	73.2	233	194	145
SD	5.0	7.2	0.052	3.8	4.6	0.40	4.5	5.2	17	14	10
SEM	0.9	1.4	0.010	0.7	0.9	0.07	0.8	1.0	3	3	2

Appendix 7·1

Study 4: Informed consent

INFORMED CONSENT

DE MONTFORT
UNIVERSITY
BEDFORD

INFORMED CONSENT FORM

1 Purpose To assess possible gender differences in oxygen handling capabilities at four sub-maximal running speeds.

2 Procedures The laboratory procedures include:

- assessment of stature and body mass
- estimation of body fat % using skinfold measurements
- determination of sub-maximal oxygen uptake at four running speeds via a treadmill run.

3 Queries I will be pleased to answer any queries that you might have.

4 Withdrawal You are free at any time to withdraw consent and stop participating.

5 Confidentiality Your identity will be strictly confidential and all data will be anonymous.

6 Consent I . . . . have read and understood the information on this form and agree to take part in the study.

Signed: . . . . Date: . . . .

Paddy Johnson
Home:01234 447842
Work: 01234 793378

Appendix 7·2

Study 4: Descriptive and study criteria data.

Study 4: Descriptive and study criteria data.

Male (n = 17)

Subject	Age (yrs)	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailliac (mm)	Sum (mm)	Fat (%)	Fat mass (kg)	FFM (kg)	VO_{2max} ($l \cdot min^{-1}$)	Experience (yrs)	Injury	Full Training
1	16.9	65.5	1.709	5.3	11.1	10.1	20.9	47.4	18.6	12.2	53.3	4.45	4	no	yes
2	18.1	59.0	1.801	3.2	6.4	6.3	7.5	23.4	10.1	6.0	53.0	4.24	6	no	yes
3	26.0	69.4	1.702	4.3	10.8	8.4	8.0	31.5	13.3	9.2	60.2	4.78	3	no	yes
4	21.1	75.2	1.936	3.0	4.8	8.0	7.9	23.7	9.9	7.4	67.8	5.73	10	no	yes
5	28.9	61.8	1.710	2.8	6.8	7.1	7.8	24.5	10.3	6.4	55.4	4.69	8	no	yes
6	19.5	64.8	1.765	3.6	8.0	8.3	10.5	30.4	13.2	8.6	56.2	5.00	5	no	yes
7	28.2	68.2	1.807	5.0	11.0	12.1	15.5	43.6	17.2	11.7	56.5	4.69	4	no	yes
8	20.2	75.8	1.849	6.7	13.0	11.6	16.2	47.5	18.2	13.8	62.0	4.98	5	no	yes
9	19.5	68.6	1.757	4.2	7.6	8.2	12.0	32.0	13.8	9.5	59.1	4.87	3	no	yes
10	24.8	68.4	1.74	3.8	7.8	11.1	19.3	42.0	16.8	11.5	56.9	4.28	3	no	yes
11	19.6	78.0	1.91	3.0	5.2	6.8	5.0	20.0	8.3	6.5	71.5	6.41	9	no	yes
12	34.6	67.9	1.74	3.1	4.6	7.5	8.0	23.2	9.7	6.6	61.3	5.03	23	no	yes
13	25.7	69.5	1.83	2.8	4.8	6.8	5.0	19.4	7.6	5.3	64.2	5.74	4	no	yes
14	21.6	74.9	1.79	3.3	4.5	8.4	6.8	23.0	9.6	7.2	67.7	5.84	8	no	yes
15	25.8	76.5	1.90	3.1	5.9	6.9	10.4	26.3	11.2	8.6	67.9	5.68	9	no	yes
16	21.0	70.2	1.79	3.8	8.8	8.8	13.8	35.2	14.6	10.2	60.0	5.01	7	no	yes
17	23.4	69.3	1.81	3.1	6.1	9.3	7.8	26.3	11.2	7.8	61.5	5.09	10	no	yes
Mean	23.2	69.6	1.80	3.8	7.5	8.6	10.7	30.6	12.6	8.7	60.9	5.09	7		
SD	4.6	5.2	0.07	1.1	2.6	1.8	4.8	9.4	3.5	2.5	5.5	0.60	5		

Study 4: Descriptive and study criteria data.

Female (n = 17)

Subject	Age (yrs)	Mass (kg)	Stature (m)	Biceps (mm)	Triceps (mm)	Subscap (mm)	Suprailliac (mm)	Sum (mm)	Fat (%)	Fat mass (kg)	FFM (kg)	VO_{2max} ($l\cdot min^{-1}$)	Experience (yrs)	Injury	Full Training
1	16.6	47.4	1.70	4.6	7.2	7.1	7.7	26.6	17.7	8.4	39.0	2.84	4	no	yes
2	15.9	45.2	1.66	4.4	7.2	6.6	8.8	27.0	20.8	9.4	35.8	2.76	4	no	yes
3	22.1	68.3	1.64	7.3	18.8	12.5	18.7	57.3	28.8	19.7	48.6	3.90	12	no	yes
4	22.6	52.0	1.58	7.1	14.5	18.9	13.0	53.5	27.8	14.5	37.5	2.96	12	no	yes
5	16.6	58.0	1.55	8.3	17.4	9.5	19.8	55.0	27.4	15.9	42.1	3.37	3	no	yes
6	31.9	49.9	1.58	4.2	15.1	10.0	6.8	36.1	24.2	12.1	37.8	3.19	12	no	yes
7	23.2	54.2	1.58	4.4	12.2	11.1	10.1	37.8	22.9	12.4	41.8	3.34	7	no	yes
8	19.5	61.0	1.61	5.4	14.2	10.5	17.1	47.2	25.3	15.4	45.6	3.49	4	no	yes
9	21.9	60.4	1.65	4.4	10.0	8.8	14.3	37.5	22.8	13.8	46.6	4.25	10	no	yes
10	33.6	56.3	1.62	2.8	8.9	6.0	5.6	23.3	16.2	9.1	47.1	3.25	12	no	yes
11	17.9	60.4	1.82	3.8	8.4	5.8	7.4	25.4	17.1	10.3	50.1	3.83	6	no	yes
12	30.2	61.7	1.61	6.8	14.6	9.6	12.4	43.4	24.8	15.3	46.4	3.36	4	no	yes
13	16.6	48.7	1.62	4.6	14.6	7.8	9.4	36.4	21.9	10.7	38.0	3.05	6	no	yes
14	27.4	59.3	1.71	4.4	10.6	10.0	8.6	33.6	21.2	12.6	46.7	3.27	14	no	yes
15	24.7	52.0	1.59	3.8	11.6	7.9	5.0	28.3	18.8	9.8	42.2	2.98	15	no	yes
16	36.2	64.9	1.70	7.2	18.8	9.3	9.6	44.9	25.3	16.4	48.4	3.61	10	no	yes
17	20.2	47.6	1.70	4.5	9.0	7.1	11.5	32.1	20.6	9.8	37.8	2.85	5	no	yes
Mean	23.4	55.7	1.64	5.2	12.5	9.3	10.9	38.0	22.6	12.7	43.0	3.31	8		
SD	6.4	6.7	0.07	1.6	3.8	3.1	4.6	11.0	3.9	3.2	4.7	0.41	4		

Appendix 7·3

Study 4: Sub-maximal oxygen uptake data.

Study 4: Sub-maximal oxygen uptake data - 2.72 m·s^{-1}

Male (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake at 2.72 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.749}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	65.5	53.3	12.2	1.96	29.9	85.7	270.7	127.7
2	59.0	53.0	6.0	1.90	32.2	89.8	263.1	138.7
3	69.4	60.2	9.2	1.73	24.9	72.4	225.0	110.0
4	75.2	67.8	7.4	2.26	30.1	89.1	277.0	137.6
5	61.8	55.4	6.4	2.16	35.0	98.6	292.6	152.2
6	64.8	56.2	8.6	1.76	27.2	77.5	236.7	118.2
7	68.2	56.5	11.7	2.12	31.1	89.9	284.5	134.3
8	75.8	62.0	13.8	2.28	30.1	89.4	292.2	131.3
9	68.6	59.1	9.5	2.40	35.0	101.3	314.8	153.7
10	68.4	56.9	11.5	2.07	30.3	87.6	276.7	131.0
11	78.0	71.5	6.5	2.30	29.5	88.2	274.4	137.7
12	67.9	61.3	6.6	1.88	27.7	80.0	242.2	123.8
13	69.5	64.2	5.3	2.01	28.9	84.1	253.1	131.6
14	74.9	67.7	7.2	2.49	33.2	98.4	305.3	152.4
15	76.5	67.9	8.6	2.45	32.0	95.4	300.0	146.1
16	70.2	60.0	10.2	1.98	28.2	82.2	257.9	124.0
17	69.3	61.5	7.8	2.18	31.5	91.3	280.3	140.3
Mean	69.6	60.9	8.7	2.11	30.4	88.3	273.3	134.7
SD	5.2	5.5	2.5	0.23	2.7	7.7	24.7	12.2
SEM	1.3	1.3	0.6	0.06	0.6	1.9	6.0	3.0

Study 4: Sub-maximal oxygen uptake data - 3.17 m·s^{-1}

Male (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake at 3.17 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	65.5	53.3	12.2	2.30	35.1	100.5	317.6	149.8
2	59.0	53.0	6.0	2.09	35.4	98.8	289.4	152.6
3	69.4	60.2	9.2	1.94	28.0	81.2	252.3	123.4
4	75.2	67.8	7.4	2.75	36.6	108.4	337.1	167.5
5	61.8	55.4	6.4	2.38	38.5	108.6	322.4	167.7
6	64.8	56.2	8.6	2.10	32.4	92.5	282.4	141.1
7	68.2	56.5	11.7	2.43	35.6	103.0	326.1	153.9
8	75.8	62.0	13.8	2.57	33.9	100.7	329.3	148.0
9	68.6	59.1	9.5	2.61	38.0	110.2	342.3	167.1
10	68.4	56.9	11.5	2.51	36.7	106.2	335.6	158.9
11	78.0	71.5	6.5	2.57	32.9	98.6	306.6	153.9
12	67.9	61.3	6.6	2.34	34.5	99.6	301.4	154.1
13	69.5	64.2	5.3	2.38	34.3	99.6	299.7	155.9
14	74.9	67.7	7.2	2.90	38.7	114.6	355.6	177.5
15	76.5	67.9	8.6	2.68	35.1	104.3	328.2	159.8
16	70.2	60.0	10.2	2.31	32.9	95.9	300.9	144.6
17	69.3	61.5	7.8	2.49	35.9	104.3	320.2	160.2
Mean	69.6	60.9	8.7	2.43	35.0	101.6	314.5	155.0
SD	5.2	5.5	2.5	0.25	2.6	7.7	25.3	12.3
SEM	1.3	1.3	0.6	0.06	0.6	1.9	6.1	3.0

Study 4: Sub-maximal oxygen uptake data - 3.61 m·s^{-1}

Male (n = 17)

Subject	Mass	FFM	Fat mass	Oxygen uptake at 3.61 m·s^{-1}				
	(kg)	(kg)	(kg)	(l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	65.5	53.3	12.2	2.58	39.4	112.8	356.3	168.1
2	59.0	53.0	6.0	2.32	39.3	109.6	321.2	169.3
3	69.4	60.2	9.2	2.17	31.3	90.8	282.2	138.0
4	75.2	67.8	7.4	3.08	41.0	121.4	377.5	187.6
5	61.8	55.4	6.4	2.74	44.3	125.1	371.1	193.1
6	64.8	56.2	8.6	2.42	37.3	106.6	325.4	162.6
7	68.2	56.5	11.7	2.81	41.2	119.2	377.1	178.0
8	75.8	62.0	13.8	3.02	39.9	118.4	387.0	173.9
9	68.6	59.1	9.5	2.96	43.1	125.0	388.2	189.5
10	68.4	56.9	11.5	2.82	41.2	119.3	377.0	178.5
11	78.0	71.5	6.5	2.80	35.9	107.4	334.1	167.6
12	67.9	61.3	6.6	2.52	37.1	107.2	324.6	166.0
13	69.5	64.2	5.3	2.72	39.2	113.8	342.5	178.1
14	74.9	67.7	7.2	3.35	44.7	132.4	410.7	205.0
15	76.5	67.9	8.6	3.22	42.1	125.4	394.3	192.0
16	70.2	60.0	10.2	2.78	39.6	115.4	362.1	174.0
17	69.3	61.5	7.8	2.75	39.7	115.2	353.6	177.0
Mean	69.6	60.9	8.7	2.77	39.8	115.6	357.9	176.4
SD	5.2	5.5	2.5	0.31	3.2	9.7	32.8	15.1
SEM	1.3	1.3	0.6	0.07	0.8	2.4	8.0	3.7

Study 4: Sub-maximal oxygen uptake data - 4.05 m·s^{-1}

Male (n = 17)

Subject	Mass	FFM	Fat mass	Oxygen uptake - 4.05 m·s^{-1}				
	(kg)	(kg)	(kg)	(l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.74}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	65.5	53.3	12.2	3.00	45.8	131.1	414.3	195.4
2	59.0	53.0	6.0	2.71	45.9	128.1	375.2	197.8
3	69.4	60.2	9.2	2.44	35.2	102.1	317.3	155.2
4	75.2	67.8	7.4	3.52	46.8	138.7	431.4	214.4
5	61.8	55.4	6.4	3.28	53.1	149.7	444.3	231.2
6	64.8	56.2	8.6	2.83	43.7	124.7	380.6	190.1
7	68.2	56.5	11.7	3.36	49.3	142.5	450.9	212.8
8	75.8	62.0	13.8	3.68	48.6	144.3	471.6	211.9
9	68.6	59.1	9.5	3.57	52.0	150.7	468.2	228.6
10	68.4	56.9	11.5	3.41	49.9	144.3	455.9	215.8
11	78.0	71.5	6.5	3.09	39.6	118.5	368.7	185.0
12	67.9	61.3	6.6	2.92	43.0	124.2	376.1	192.3
13	69.5	64.2	5.3	3.01	43.3	125.9	379.0	197.1
14	74.9	67.7	7.2	3.86	51.5	152.6	473.3	236.2
15	76.5	67.9	8.6	3.47	45.4	135.1	424.9	206.9
16	70.2	60.0	10.2	3.14	44.7	130.3	409.0	196.6
17	69.3	61.5	7.8	3.02	43.6	126.5	388.3	194.3
Mean	69.6	60.9	8.7	3.19	46.0	133.5	413.5	203.6
SD	5.2	5.5	2.5	0.37	4.6	13.2	44.4	19.6
SEM	1.3	1.3	0.6	0.09	1.1	3.2	10.8	4.8

Study 4: Sub-maximal oxygen uptake data - 2.72 m·s^{-1}

Female (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake - 2.72 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	47.4	39.0	8.4	1.47	31.0	81.8	237.2	124.8
2	45.2	35.8	9.4	1.34	29.6	77.3	225.7	118.0
3	68.3	48.6	19.7	1.84	26.9	77.9	266.0	111.3
4	52.0	37.5	14.5	1.69	32.5	87.8	277.9	132.0
5	58.0	42.1	15.9	2.30	39.7	110.1	357.2	162.9
6	49.9	37.8	12.1	1.93	38.7	103.4	316.2	156.5
7	54.2	41.8	12.4	1.76	32.5	88.6	274.4	133.2
8	61.0	45.6	15.4	1.82	29.8	83.9	271.8	123.6
9	60.4	46.6	13.8	2.20	36.4	102.2	324.8	151.7
10	56.3	47.1	9.1	1.67	29.7	81.8	245.2	124.2
11	60.4	50.1	10.3	1.87	31.0	86.8	266.4	131.0
12	61.7	46.4	15.3	1.86	30.1	85.0	275.3	125.2
13	48.7	38.0	10.7	1.54	31.6	84.0	251.6	127.6
14	59.3	46.7	12.6	1.87	31.5	88.0	275.8	131.5
15	52.0	42.2	9.8	1.70	32.7	88.3	263.7	134.0
16	64.9	48.4	16.4	1.99	30.7	87.6	288.3	127.8
17	47.6	37.8	9.8	1.46	30.7	81.1	239.4	123.4
Mean	55.7	43.0	12.7	1.78	32.1	88.0	273.9	131.7
SD	6.7	4.7	3.2	0.25	3.3	9.0	33.5	13.5
SEM	1.6	1.1	0.8	0.06	0.8	2.2	8.1	3.3

Study 4: Sub-maximal oxygen uptake data - 3.17 m·s^{-1}

Female (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake - 3.17 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	47.4	39.0	8.4	1.83	38.6	101.9	295.3	155.4
2	45.2	35.8	9.4	1.57	34.7	90.6	264.4	138.2
3	68.3	48.6	19.7	2.33	34.1	98.7	336.9	140.9
4	52.0	37.5	14.5	2.05	39.4	106.5	337.1	160.1
5	58.0	42.1	15.9	2.56	44.1	122.6	397.6	181.3
6	49.9	37.8	12.1	2.15	43.1	115.2	352.3	174.4
7	54.2	41.8	12.4	2.11	38.9	106.3	329.0	159.7
8	61.0	45.6	15.4	2.33	38.2	107.4	347.9	158.3
9	60.4	46.6	13.8	2.47	40.9	114.7	364.6	170.3
10	56.3	47.1	9.1	1.93	34.3	94.5	283.4	143.5
11	60.4	50.1	10.3	2.25	37.3	104.5	320.6	157.6
12	61.7	46.4	15.3	2.25	36.5	102.8	333.0	151.4
13	48.7	38.0	10.7	1.86	38.2	101.5	303.9	154.1
14	59.3	46.7	12.6	2.20	37.1	103.6	324.4	154.7
15	52.0	42.2	9.8	1.91	36.7	99.2	296.3	150.5
16	64.9	48.4	16.4	2.35	36.2	103.5	340.4	150.9
17	47.6	37.8	9.8	1.62	34.1	90.0	265.7	137.0
Mean	55.7	43.0	12.7	2.10	37.8	103.7	323.1	155.2
SD	6.7	4.7	3.2	0.28	2.9	8.4	35.1	12.1
SEM	1.6	1.1	0.8	0.07	0.7	2.0	8.5	2.9

Study 4: Sub-maximal oxygen uptake data - 3.61 m·s^{-1}

Female (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake - 3.61 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	47.4	39.0	8.4	2.21	46.6	123.0	356.6	187.6
2	45.2	35.8	9.4	1.92	42.5	110.8	323.3	169.1
3	68.3	48.6	19.7	2.73	40.0	115.6	394.7	165.1
4	52.0	37.5	14.5	2.26	43.5	117.4	371.7	176.5
5	58.0	42.1	15.9	3.02	52.1	144.6	469.1	213.9
6	49.9	37.8	12.1	2.39	47.9	128.0	391.6	193.8
7	54.2	41.8	12.4	2.38	43.9	119.9	371.1	180.2
8	61.0	45.6	15.4	2.88	47.2	132.8	430.1	195.6
9	60.4	46.6	13.8	2.91	48.2	135.1	429.6	200.6
10	56.3	47.1	9.1	2.22	39.5	108.7	326.0	165.1
11	60.4	50.1	10.3	2.50	41.4	116.1	356.2	175.1
12	61.7	46.4	15.3	2.50	40.5	114.3	370.0	168.3
13	48.7	38.0	10.7	2.30	47.2	125.5	375.8	190.6
14	59.3	46.7	12.6	2.53	42.7	119.1	373.1	177.9
15	52.0	42.2	9.8	2.36	45.4	122.6	366.1	186.0
16	64.9	48.4	16.4	2.73	42.1	120.2	395.4	175.3
17	47.6	37.8	9.8	1.92	40.4	106.6	314.9	162.3
Mean	55.7	43.0	12.7	2.46	44.2	121.2	377.4	181.4
SD	6.7	4.7	3.2	0.32	3.6	9.8	39.8	14.3
SEM	1.6	1.1	0.8	0.08	0.9	2.4	9.7	3.5

Study 4: Sub-maximal oxygen uptake data - 4.05 m·s^{-1}

Female (n = 17)

Subject	Mass (kg)	FFM (kg)	Fat mass (kg)	Oxygen uptake - 4.05 m·s^{-1} (l·min^{-1})	(ml·BM^{-1}·min^{-1})	(ml·BM$^{-0.75}$·min^{-1})	(ml·FFM$^{-0.498}$·min^{-1})	(ml·FFM$^{-0.63}$·exp(0.018·FM)·min^{-1})
1	47.4	39.0	8.4	2.62	55.3	145.9	422.7	222.5
2	45.2	35.8	9.4	2.18	48.2	125.8	367.1	192.0
3	68.3	48.6	19.7	3.04	44.5	128.8	439.5	183.8
4	52.0	37.5	14.5	2.58	49.6	134.0	424.3	201.5
5	58.0	42.1	15.9	3.24	55.9	155.1	503.2	229.5
6	49.9	37.8	12.1	2.69	53.9	144.1	440.7	218.2
7	54.2	41.8	12.4	2.64	48.7	133.0	411.6	199.8
8	61.0	45.6	15.4	3.35	54.9	154.4	500.3	227.5
9	60.4	46.6	13.8	3.31	54.8	153.7	488.7	228.2
10	56.3	47.1	9.1	2.56	45.5	125.4	375.9	190.4
11	60.4	50.1	10.3	2.75	45.5	127.7	391.8	192.7
12	61.7	46.4	15.3	2.89	46.8	132.1	427.7	194.5
13	48.7	38.0	10.7	2.52	51.7	137.5	411.7	208.8
14	59.3	46.7	12.6	2.94	49.6	138.4	433.6	206.8
15	52.0	42.2	9.8	2.72	52.3	141.3	421.9	214.3
16	64.9	48.4	16.4	3.08	47.5	135.6	446.1	197.8
17	47.6	37.8	9.8	2.17	45.6	120.5	355.9	183.5
Mean	55.7	43.0	12.7	2.78	50.0	137.3	427.2	205.4
SD	6.7	4.7	3.2	0.35	3.9	10.6	42.4	15.6
SEM	1.6	1.1	0.8	0.08	0.9	2.6	10.3	3.8